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NUTRIENT TRANSPORT AND DISSOLVED OXYGEN BUDGET STUDIES IN THE POTOMAC ESTUARY

Leo J. Clark, et al

Environmental Protection Agency
Annapolis, Maryland

October 1972

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Technical Report 37
Annapolis Field Office
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October 1972

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PREFACE

The ability to simulate, mathematically, the historical dissolved oxygen (DO) distribution in a watercourse is quite an achievement, especially when most of the known components of the DO budget are quantitatively defined and incorporated in the analysis. This ability is in fact required to predict future changes, including standards compliance, in the dissolved oxygen content of a lake, stream, or estuary due to municipal or industrial growth.

While the classical Streeter-Phelps study of the Ohio River in 1924 initially established the basic relationships governing dissolved oxygen, the evaluation of the oxygen budget is no longer based solely on the biochemical oxyged demand (BOD) and reaeration. Sanitary engineers have intruded into the biologist's domain by attempts to determine in mathematical terms the effects of nutrient materials, specifically nitrogen and phosphorus, on the density and extent of algal blooms and the algae's subsequent effect on the DO budget. A strong interdependence exists among nitrogen, phosphorus, algae and dissolved oxygen, and although only a rudimentary approach was ventured, the Annapolis Field Office (AFO) of the Environmental Protection Agency (EPA) has mathematically modeled this interrelationship in the upper Potomac Estuary.

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CHAPTER I

INTRODUCTION

A. PURPOSE AND SCOPE

The importance of mathematical models as a water quality management "tool" is widely acknowledged. Models have evolved from the one dimensional steady-state type capable of simulating only relatively conservative constituents such as tracer dye or chlorides to time-dependent models linking BOD and DO and finally to multi-constituent models capable of (1) elaborate "feedback" linkage between the various constituents, (2) not only first-order kinetics but any mathematically describable reaction, and (3) incorporating tidal aspects to permit "real-time" hydraulic and quality predictions.

The purpose of this report is to present the approach taken by AFO to model a portion of the nitrogen cycle, phosphorus deposition, and the occurrence of algal blooms as measured by chlorophyll a; as well as the effects of carbonaceous, nitrogenous, and benthic oxygen demand; algal photosynthesis, respiration and decay; and reaeration on the dissolved oxygen resources in the upper Potomac Estuary. Basically, this approach entailed a feedback model similar to the one proposed by Thomann [1] and a procedure whereby individual reaction rates, based on a visual comparison of observed and simulated data, were estimated. Upon determining the appropriate rates, the models' reliability to predict DO distributions was investigated.

The EPA Dynamic Estuary Model [2] was modified to incorporate the necessary reactions describing nitrogen and phosphorus transport and

most sources and sinks of dissolved oxygen. This model was used primarily to simulate short-term, pseudo-steady-state conditions. DECS III, an average tidal model, [3] was used to simulate nitrogen and phosphorus behavior over an annual cycle. Both of these models successfully simulated (1) a tracer dye distribution following a 13-day continuous release and (2) seasonal chlorinity changes in the Potomac Estuary [4] prior to the more complex modeling discussed in this report. In addition, the two models were used to investigate the role of nutrients in the eutrophication process and to establish maximum allowable nutrient and ultimate oxygen demand loadings for different zones of the Potomac Estuary [5].

The entire Potomac Estuary is included in the framework of the mathematical models. Since uncertainties arise when applying either model to the mesohaline portion of the estuary, most of the analyses will pertain to the freshwater region of the Potomac with the major emphasis placed on the critical area immediately downstream from Washington, D. C.

B. ACKNOWLEDGEMENTS

Special recognition has been given to the Steuart Petroleum Company, Piney Point, Maryland, for their extensive cooperation and assistance in performing all sampling during AFO's 1969-70 nutrient transport study of the Potomac Estuary. This report could not have been completed as promptly without such sampling assistance.

CHAPTER II

SUMMARY AND CONCLUSIONS

During 1970, the Annapolis Field Office embarked on a mathematical modeling study of the Potomac Estuary utilizing a 1965-70 data base to (1) predict nitrogen and phosphorus distributions during both a relatively short time period (steady-state) and over an annual cycle, (2) define the various reaction rates, including temperature effects, directly influencing nutrient transport, (3) evaluate the role of both nitrogen and phosphorus in the existing eutrophication problem and develop predictive capabilities for algal standing crop, (4) formulate a DO budget model incorporating algal effects in addition to biological oxidation and reaeration and (5) determine the maximum allowable loadings of nitrogen, phosphorus and carbon (BOD) that will maintain water quality commensurate with existing standards. The findings evolved during data analysis, model development and verification are as follows:

1) There are currently eighteen wastewater treatment facilities in the Washington Metropolitan Area that discharge total BOD_5, phosphorus (P) and nitrogen (N) loadings to the upper Potomac Estuary of 143,000 lbs/day, 25,000 lbs/day, and 60,000 lbs/day, respectively.

2) During the period from February 1969 to February 1970 the average nutrient contributions from the upper Potomac River Basin were, phosphorus (as P), 4,580 lbs/day, and nitrogen (as N), 59,000 lbs/day. These loadings correspond to an average freshwater flow of 6,900 cfs.

3) The median loadings contributed from urban and suburban runoff to the upper Potomac Estuary are given below:

Parameter	Loading (lbs/day)
BOD_5	12,500
Phosphorus (P)	850
Nitrogen (N)	4,070

4) Using weekly nitrogen data collected in the Potomac Estuary from February 1969 to July 1970 the following conclusions were drawn:

a) Maximum ammonia concentrations of 2.0 mg/l were observed on numerous occasions near the major wastewater discharges. A drastic reduction in ammonia, attributable to nitrification, occurred between the Woodrow Wilson Bridge and Indian Head under high temperature conditions.

b) The reduction in ammonia concentrations were accompanied by high levels of nitrate nitrogen, often approaching 2.0 mg/l. Farther downstream, between Indian Head and Smith Point, a significant decrease in nitrate, due to biological (algal) uptake, occurred during the summer and fall months.

c) Organic nitrogen concentrations were extremely high (3.0 mg/l) in the Potomac during the late summer and early fall when algal blooms were profuse.

5) Utilizing the EPA Dynamic Estuary Model and data from thirteen intensive sampling runs conducted under steady-state conditions, nitrification rates required for model verification varied from 0.005/day

to 0.4/day depending on temperature. At 20°C, the nitrification rate was 0.084/day (base e).

6) Reasonable agreement between the thirteen sets of observed nitrate data and model predictions was obtained when algal uptake rates varied from 0.01/day to 0.13/day with a 20°C value of 0.037/day (base e). A definite temperature vs algal uptake rate relationship was again indicated.

7) A modified version of DECS III that incorporated the verified reaction rates and temperature effects discussed above accurately simulated the basic seasonal trends and spatial distributions of ammonia and nitrate nitrogen observed during the period February 1969 to July 1970.

8) A modified version of the EPA Dynamic Estuary Model which converted losses of nitrate nitrogen to algal biomass based upon elemental composition ratios was used to predict bloom conditions in the Potomac as measured by chlorophyll a. Eight separate sets of chlorophyll data representing different flow and temperature conditions were simulated satisfactorily with this model, thus indicating the importance of inorganic nitrogen as a possible growth-rate-limiting nutrient.

9) Phosphorus data measured weekly in the Potomac Estuary during 1969-70 revealed the following:

a) The distribution of both inorganic and total phosphorus was markedly similar during the study period. Maximum concentrations of 2.0 mg/l and 4.0 mg/l, respectively, were recorded between Bellevue and Piscataway Creek with concentrations diminishing farther downstream.

b) Although high freshwater flow periods contributed an excessive phosphorus load, the adsorption of phosphorus onto silt particles accompanying these high flows and its eventual deposition actually reduced the phosphorus content in the upper Potomac Estuary.

c) During high temperature periods, inorganic phosphorus concentrations decreased appreciably downstream from Piscataway Creek as a result of biological uptake by phytoplankton and chemical deposition.

10) A modified version of the DEM having second order kinetics was utilized to simulate fourteen sets of prototype data and evaluate the phosphorus loss rate. Based on these simulation studies the loss rates required for model verification ranged from 0.005 gr/day to 0.04 gr/day, varying with temperature. The rate derived from a regression analysis for 20°C was 0.0218 gr/day.

11) A modified version of DECS III that again incorporated second order kinetics and the verified rates given above adequately simulated the interseasonal phosphorus distributions throughout the Potomac Estuary as observed between February 1969 and July 1970.

12) A series of model runs (DEM) that related phosphorus loss to algal productivity was made in order to delineate biological uptake from physical deposition of phosphorus and to acquire a better understanding of the significance of phosphorus as a possible growth-rate-limiting nutrient. Based on these runs, it appeared that only 10 to 20 percent of the phosphorus losses were attributable to uptake by algal cells whereas 80 to 90 percent represented deposition to the bottom sediments.

13) The DO budget model employed by AFO in its study of the Potomac Estuary consisted of the following five linkages:

a) oxidation of carbonaceous matter

b) oxidation of nitrogenous matter

c) oxygen production and respiration of simulated algal standing crops based upon the nitrogen cycle

d) benthic demand, and

e) atmospheric reaeration

14) The aforementioned DO model proved capable of simulating nine different observed conditions between 1965 and 1970 when freshwater flows and temperature ranged from 185 cfs to 8800 cfs, and 19°C to 30°C, respectively. In order to achieve a meaningful verification of this model it was necessary to base all simulation runs on the following reaction rates and other related assumptions:

Process

a) Carbonaceous oxidation - 0.17 (base e - 20°C)

b) Nitrogenous oxidation - 0.084 (base e - 20°C)

c) Reaeration - O'Connor-Dobbins Formulation

d) Algal oxygen production rate - 0.012 mgO_2/hr/µg chloro a

e) Algal respiration rate - 0.0008 mgO_2/hr/µg chloro a

f) Euphotic Zone - 2 feet

g) Respiration Depth - full depth of water column

h) Algal oxygen production period - 12 hours

i) Algal respiration period - 24 hours

j) Benthic demand - 1.0 $grO_2/meter^2$/day

15) In order to determine the relative importance of the various rates incorporated in the DO budget model, a detailed sensitivity analysis was performed. The following conclusions were drawn based upon the results of this sensitivity analysis:

a) The predicted critical DO deficit is markedly sensitive to the carbonaceous oxidation rate assigned in the model. Since the mass of unoxidized nitrogen in the Potomac is considerably less than that of carbon, the model predictions for DO were not significantly affected when a comparable range in nitrification rates was inputted.

b) Increasing the algal photosynthesis rate or decreasing the respiration rate produced basically comparable results insofar as model predictions are concerned. Both the critical deficit and that portion of the predicted profile representing DO recovery were drastically affected when a change in either rate was instituted.

c) A displacement of the entire predicted DO profile by a substantial amount was noted when different benthic demand rates were used indicating significant model sensitivity.

d) Various expressions for computing the reaeration rate (i.e. O'Connor-Dobbins, Churchill and Langbein's Egs) were used in the model; however, no changes in predicted DO data were detected.

CHAPTER III

DESCRIPTION OF STUDY AREA

The Potomac River Basin, with a drainage area of 14,670 square miles, is the second largest watershed in the Middle Atlantic States. From its headwaters on the eastern slope of the Applachian Mountains near the historic Fairfax Stone, the Potomac flows first northeasterly then generally southeasterly some 400 miles to the Chesapeake Bay. The Potomac traverses the Piedmont Plateau until it reaches the Fall Line near Washington, D. C. Below the Fall Line, the Potomac is tidal, extending 114 miles southeastward and discharging into the Chesapeake Bay.

The tidal portion is several hundred feet in width in its uppermost reach near Washington and broadens to nearly six miles at its mouth. A shipping channel with a minimum depth of 24 feet is maintained upstream from the mouth to Washington. Except for this channel and a few short reaches where depths up to 100 feet occur, the tidal portion is relatively shallow with an average depth of approximately 18 feet. The mean tidal range is approximately 1.4 feet near the Chesapeake Bay and 2.9 feet in the vicinity of Washington. The lag time for the tidal phase between Chesapeake Bay and Washington is approximately 6.5 hours. The entire Potomac Estuary is characterized by numerous tidal embayments, generally less than 5 feet in depth, some of which are quite large in area.

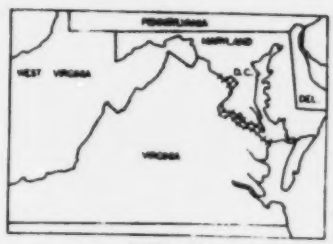
Of the 3.3 million people living in the basin, approximately

2.8 million reside in the upper portion of the Potomac Estuary within the Washington Metropolitan Area. The lower area of the tidal portion, which drains 3,216 miles, is sparsely populated.

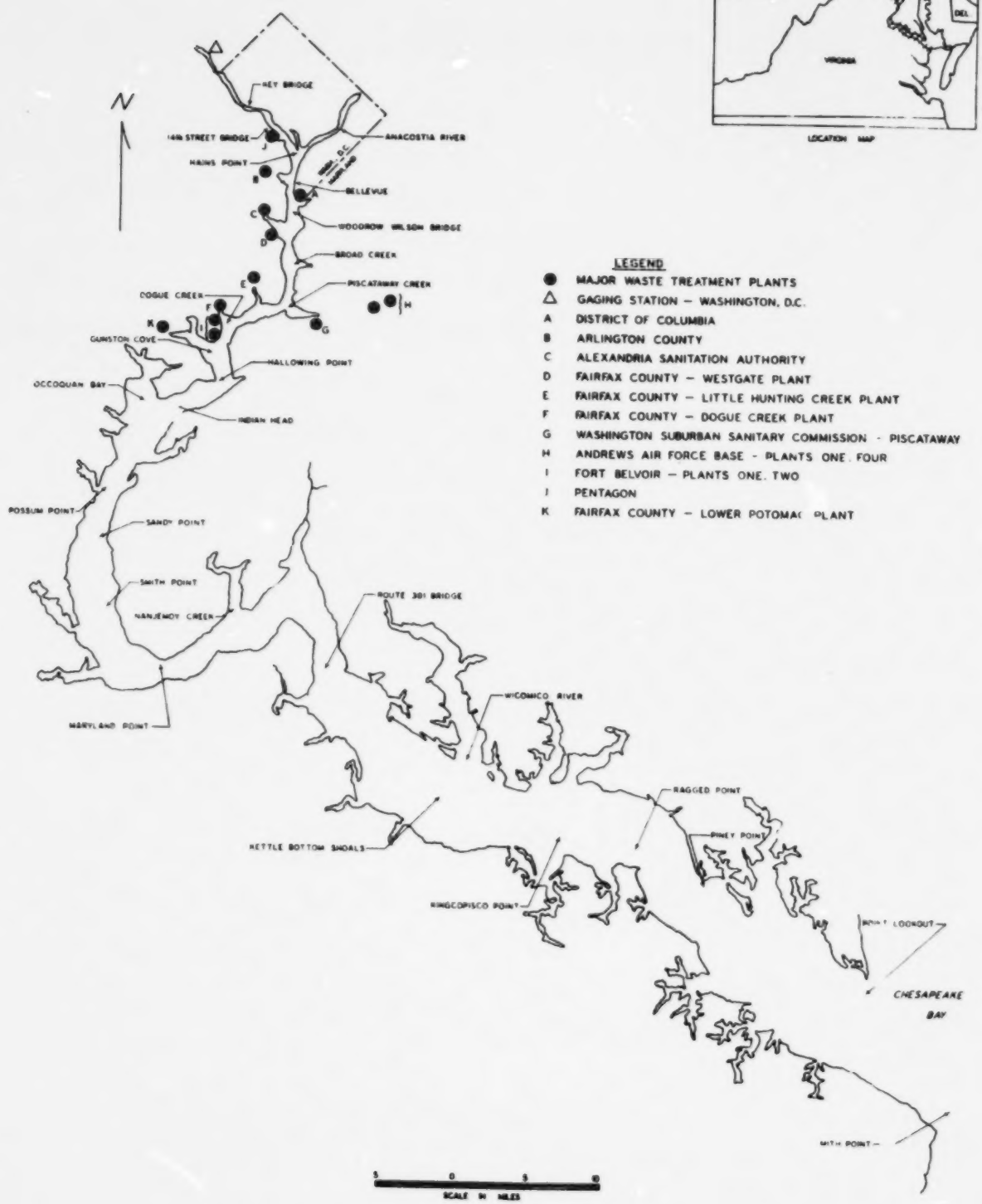
The upper reach, although tidal, contains fresh water. The middle reach is normally the transition zone from fresh to brackish water. The lower reach is saline with chloride concentrations near the Chesapeake Bay ranging from approximately 7,000 to 11,000 mg/l.

Because of minimal regulation, the Potomac is characterized by flash floods and extremely low flows. The average freshwater flow of the Potomac River near Washington, before diversions for municipal water supply, is 10,800 cubic feet per second (cfs) with a median flow of 6,500 cfs.

Detailed physical data for the Potomac Estuary, including model segmentation geometry, have been presented in a previous report [6].



LOCATION MAP



LEGEND

- ● MAJOR WASTE TREATMENT PLANTS
- △ GAGING STATION – WASHINGTON, D.C.
- A DISTRICT OF COLUMBIA
- B ARLINGTON COUNTY
- C ALEXANDRIA SANITATION AUTHORITY
- D FAIRFAX COUNTY – WESTGATE PLANT
- E FAIRFAX COUNTY – LITTLE HUNTING CREEK PLANT
- F FAIRFAX COUNTY – DOGUE CREEK PLANT
- G WASHINGTON SUBURBAN SANITARY COMMISSION - PISCATAWAY
- H ANDREWS AIR FORCE BASE - PLANTS ONE. FOUR
- I FORT BELVOIR – PLANTS ONE. TWO
- J PENTAGON
- K FAIRFAX COUNTY – LOWER POTOMAC PLANT

POTOMAC ESTUARY

FIGURE III - 1

CHAPTER IV

SOURCES OF NUTRIENTS AND OXYGEN DEMANDING SUBSTANCES

A. WASTEWATER LOADINGS

A total domestic wastewater flow of approximately 337 mgd is discharged into the Potomac River tidal system upstream from Indian Head, Maryland. Nineteen facilities currently serve approximately 2.6 million people in the Washington Metropolitan Area with the largest facility being the Blue Plains plant of the District of Columbia. Of the 337 mgd, 40.0, 26.0, and 34.0 percent originate in Maryland, Virginia, and the District of Columbia, respectively. The current BOD and nutrient loadings from each treatment facility are presented in Table IV-1. The total loadings into the upper Potomac Estuary from wastewater sources are (1) BOD_5 - 143,000 lbs/day, (2) Total Phosphorus (P) - 25,000 lbs/day, (3) Total Nitrogen (N) - 60,000 lbs/day.

There are 82 wastewater point-source discharges in the Potomac Estuary between Indian Head, Maryland, and the Chesapeake Bay. The estimated BOD, phosphorus as P, and nitrogen as N loadings from these sources are 4,000, 500, and 1,000 lbs/day, respectively. Compared to the upper reach, with a population of approximately 2.6 million, the wastewater facilities in the middle and lower reaches serve a population of approximately 50,000 and consequently account for a small percentage of the total loadings to the Potomac Estuary. Most of the discharges in this area are into tributary or embayment waters.

Table IV-1

WASTEWATER LOADINGS TO THE UPPER POTOMAC ESTUARY AND TRIBUTARIES

Facility	Population Served	Flow	BOD_5		Suspended Solids		T. Phosphorus as P	TKN	$NO_2 + NO_3$
			Untreated	Treated	Untreated	Treated	Treated	Treated	Treated
		mgd	(lbs/day)	(lbs/day)	(lbs/day)	(lbs/day)	(lbs/day)	(lbs/day)	(lbs/day)
Pentagon	10,600*	1,060	2,100	360	2,100	310	65	290	20
Arlington	247,000	19.390	33,500	5,460	37,400	14,300	1,650	1,020	1,465
Sewer Overflows D. C. System	18,300**	2.516	3,740	3,740	3,700	3,700	170	460	20
Naval Laboratory White Oaks, Md.	950*	0.095	25	7	32	12	7	25	1
District of Columbia	1,830,000	251.660	373,700	103,800	369,900	102,000	17,300	46,200	2,000
Alexandria	190,000	23.300	38,000	13,000	36,200	12,600	2,300	3,690	20
Fairfax-Westgate	124,400	11.570	11,500	10,900	9,600	8,200	1,280	1,830	40
Piscataway, WSSC	55,000	5.810	6,300	540	7,300	1,310	320	630	100
Andrews AFB No. 1	8,200*	0.820	1,200	110	770	110	45	50	30
Andrews AFB No. 4	860*	0.086	104	16	80	10	5	3	3
Naval Comm. Station Cheltenham, Md.	670*	0.067	110	15	140	14	3	2	1
Fairfax-Hunting Cr.	25,000	3.260	4,060	1,390	3,890	1,130	380	620	15
Fairfax-Dogue Cr.	20,000	2.441	4,048	915	4,010	760	270	365	20
Fort Belvoir No. 1	3,600	0.600	1,100	120	110	70	30	25	25
Fort Belvoir No. 2	18,400	2.340	3,500	380	3,800	325	175	430	20
Fairfax-Lower Potomac	100,000	11.700	16,860	2,140	19,490	3,120	760	***	***
Naval Ordnance Station Indian Head, Md.									
Site I	2,500*	0.250	155	90	200	160	12	25	1
Site II	3,600*	0.360	355	140	430	80	8	5	1
Site III	60*	0.006	2	1	2	1	1	1	1
Site IV	10*	0.001	2	1	2	1	1	1	1
TOTAL		337.332	500,361	143,125	499,146	148,213	24,782	55,672	3,784

* Based on 100 gcpd
** Based on 1% of total load to wastewater facility
*** No data available

B. CONTRIBUTIONS FROM THE UPPER POTOMAC RIVER BASIN

During the period of February 1969 to February 1970, the following average concentrations of BOD_5 and nutrients in the freshwater flow entering the upper Potomac Estuary were measured.

Parameter	Concentration (mg/l)
BOD_5	2.60
TKN as N	0.61
$NO_2 + NO_3$ as N	1.00
Phosphorus as P	0.13

Detailed analyses of the freshwater inflows from the upper Potomac River Basin at Great Falls were conducted during 1969 and 1970. The observed data, as shown in Figure IV-1, indicate the wide range of nutrient concentrations for the period of June 1969 to July 1970. The river discharge was considerably higher during the 1970 period of the study than it was for the 1969 thus resulting in higher $NO_2 + NO_3$ concentrations. Concentrations of TKN and phosphorus appeared to decrease during periods of high flow, except during periods of intense runoff.

The monthly nutrient contributions from the upper basin during the period of February 1969 through February 1970 are presented in Table IV-2. For this 13-month period, the average daily contributions of nutrients are given below:

Parameter	Contribution (lbs/day)
Total Phosphorus as P	4,580
Inorganic Phosphorus as P	2,650
TKN as N	22,410
NH_3 as N	4,590
$NO_2 + NO_3$ as N	36,700

NUTRIENT CONCENTRATIONS
POTOMAC RIVER AT GREAT FALLS

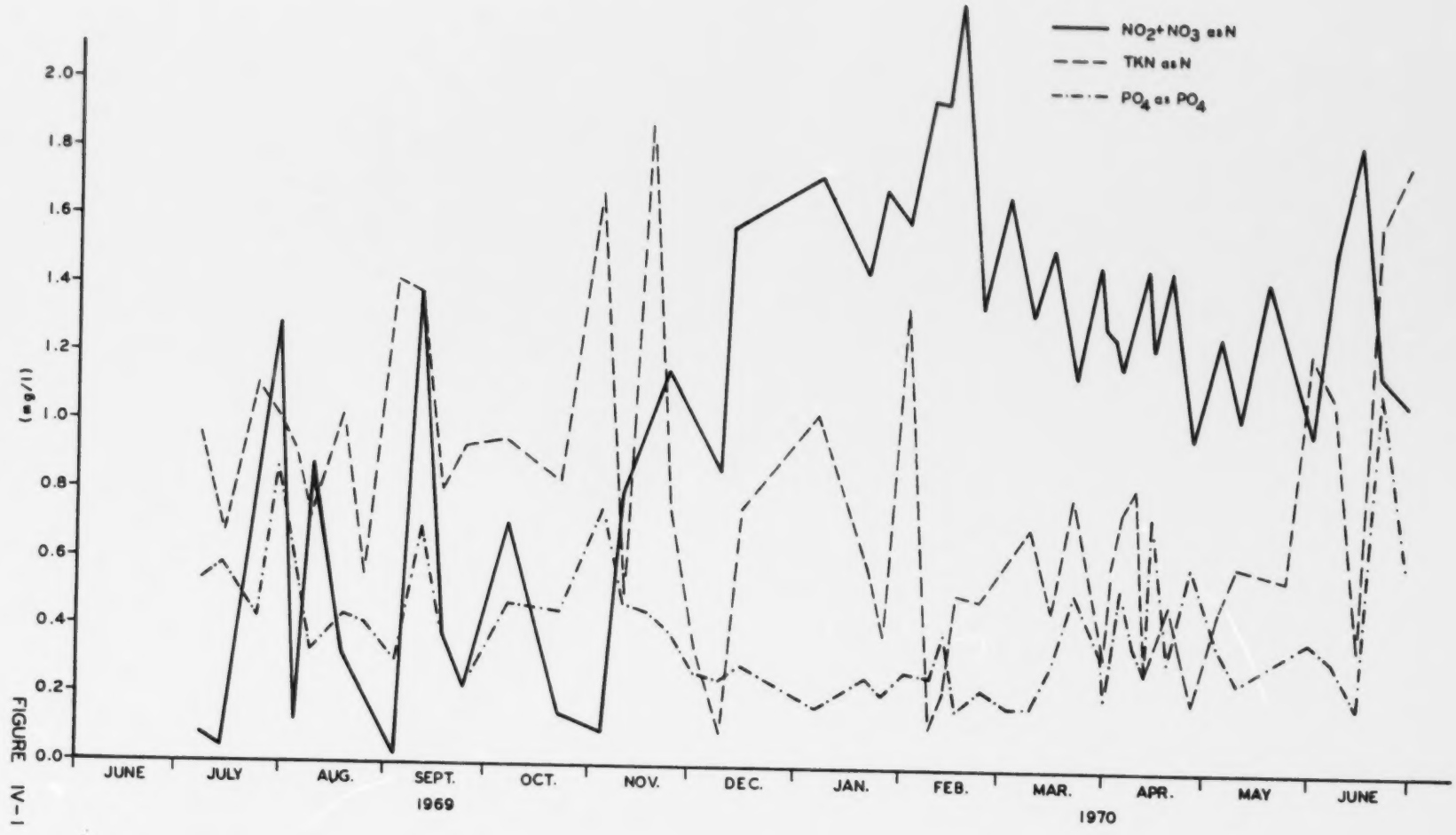


FIGURE IV-1

Table IV-2
UPPER POTOMAC RIVER BASIN CONTRIBUTIONS
(Above Great Falls)
February 1969 through February 1970

Month	Flow (cfs)	T. Phosphorus as P (lbs/day)	Inorganic Phosphorus as P (lbs/day)	TKN as N (lbs/day)	NH_3 as N (lbs/day)	$NO_2 + NO_3$ as N (lbs/day)
February	6,700	4,495	2,070	22,180	4,670	23,080
March	8,400	5,500	3,270	26,360	5,300	45,370
April	7,000	4,740	2,120	22,700	5,080	21,750
May	3,900	2,730	900	11,680	3,750	7,910
June	2,200	1,560	430	7,630	2,070	2,890
July	2,400	1,700	540	8,460	2,190	4,970
August	8,000	5,310	2,700	26,260	5,290	32,030
September	4,300	2,920	1,050	14,680	3,370	10,040
October	2,300	1,680	420	8,200	2,240	3,160
November	3,600	2,540	810	11,800	3,070	6,980
December	7,900	5,230	2,980	25,890	5,100	39,400
January	11,900	7,830	5,600	38,870	6,950	86,980
February	21,400	13,360	11,550	66,610	10,590	191,910
Average	6,900	4,580	2,650	22,410	4,590	36,700

C. SUBURBAN AND URBAN RUNOFF

A regression analysis of the river discharge and contributory loadings was applied to data from the Rock Creek and Anacostia River watersheds in the District of Columbia. Based on these regression studies and flow duration curves, yield rates in terms of lbs/day/sq mi were determined. These rates were used for the suburban areas in Virginia and Maryland as shown in Table IV-3. For the District of Columbia, additional data on stormwater and urban runoff were obtained from a study of Washington overflows [7].

The median loadings contributed from urban and suburban areas to the upper Potomac Estuary (Table IV-3) are tabulated below:

Parameter	Loadings (lbs/day)
BOD_5	12,500
TKN as N	2,560
$NO_2 + NO_3$	1,510
T. Phosphorus as P	850

The total lbs/day loadings of BOD and nutrients from suburban and urban runoff were fairly low when compared to those contributed from the upper Potomac Basin. However, the yield rates, except for nitrites and nitrates, were significantly higher for the urban and suburban area than for the upper Potomac Basin. This indicates that as an area becomes more populated, the amount of BOD, phosphorus, and TKN contributions will probably also increase.

Table IV-3
URBAN AND SUBURBAN RUNOFF CONTRIBUTIONS TO UPPER POTOMAC ESTUARY
(Great Falls to Indian Head)

	Area	Duration* Yield Rate	T. Phosphorus as P		$NO_2 + NO_3$ as N		TKN		BOD_5	
	sq mi	(percent)	lbs/day/sq mi	lbs/day	lbs/day/sq mi	lbs/day	lbs/day/sq mi	lbs/day	lbs/day/sq mi	lbs/day
Maryland	352	5	3.30	1,200	15.65	5,500	30.40	10,700	64.0	22,500
	352	50	1.00	350	1.71	600	3.20	1,100	9.6	3,400
	352	95	0.10	35	0.20	70	0.60	210	1.2	420
Virginia	300	5	3.30	1,000	15.65	4,700	30.40	9,100	64.0	19,200
	300	50	1.00	300	1.71	510	3.20	960	9.6	2,900
	300	95	0.10	30	0.20	60	0.60	180	1.2	360
District of Columbia	62	5	17.74	1,100	27.42	1,700	41.90	2,600	62.9	3,900
	62	50	3.23	200	6.45	400	8.10	500	10.0	6,200
	62	95	0.40	25	0.40	50	1.50	90	4.8	300
Total	714	5	4.62	3,300	16.66	11,900	31.37	22,400	63.86	45,600
	714	50	1.20	850	2.11	1,510	3.58	2,560	17.50	12,500
	714	95	0.12	90	0.25	180	0.67	480	1.51	1,080

* The percent of time of which a given duration of yield in lbs/day/sq mi was equaled or exceeded

CHAPTER V

FRAMEWORK FOR ANALYSIS

A. WATER QUALITY DATA

Since 1965, the Annapolis Field Office has conducted water quality sampling in the Potomac Estuary. Initially, most of the data were collected in the critical upper reach near Washington, D. C., but the area of concern has progressively lengthened to include the middle reach, where the most serious algal problems occur, and more recently the almost continuously saline lower reach.

The frequency and duration of sampling generally followed one of two patterns: (1) an intensive type survey, hopefully performed during steady-state conditions, composed of multiple sampling runs carried out each day for approximately a week's duration or (2) weekly or bi-weekly sampling over an annual cycle. The importance of the first sampling method is that relatively short-term intensive data can be employed to obtain reaction rates and, thus, be used for model verification during a period of somewhat constant temperature and freshwater flow. The EPA estuary model, due to its hydraulic solution, particularly lends itself to steady-state flow analysis. In order to verify a mathematical model over a larger time scale, to predict seasonal variations in the nitrogen and phosphorus transport mechanism, and to investigate the effects of seasonal wastewater treatment requirements, AFO with the cooperation of Steuart Petroleum Company conducted a weekly nutrient sampling program of the entire Potomac Estuary from February 1969 to May 1970. These data

will be discussed in a later section of this report. All of the intensive data have been published in separate reports [8] [9] [10].

In addition to AFO sampling, data collected by the District of Columbia's Department of Sanitary Engineering in weekly cruises in the upper Potomac Estuary were also evaluated. Certain data, which were collected during appropriate steady-state periods, were used in the rate determination and model verification studies presented in this report.

B. CHEMICAL, PHYSICAL, AND BIOLOGICAL REACTIONS

1. Nitrogen

Figure V-1 schematically shows the major reactions of the nitrogen cycle in an aquatic environment. Organic nitrogen derived primarily by biological action has many forms, with the more common being proteins, amines, purines, and urea. While certain forms (fibrous proteins) are resistant to biological degradation, others may be decomposed by biological action or, in the case of urea, hydrolyzed enzymatically into ammonia and carbon dioxide.

Ammonia nitrogen can be introduced into natural waters by sewage effluents or agricultural runoff. In addition, ammonia is released by biological decomposition of organic matter. Since it is extremely soluble in water, ammonia concentrations can become quite large. Ammonia is characterized by significant sorption (physical and chemical) properties, but more important is the fact that it can be resynthesized to organic nitrogen by aquatic plants or oxidized to nitrites by autotrophic bacteria (nitrosomonas). This latter reaction, known as nitrification, is highly dependent on temperature and pH and will proceed only under aerobic conditions. It has been reported [11] that this phase of nitrification requires 3.43 grams of oxygen for 1 gram of ammonia nitrogen to be oxidized to nitrite.

In addition to the oxidation of ammonia, nitrites are also formed by the reduction of nitrates. Further reduction by heterotrophic bacteria (denitrification) results in the release of nitrogen gas. Nitrite

nitrogen is very unstable since it can be readily oxidized by Nitrobacter bacteria to nitrates. Consequently, high concentrations of nitrite are not normally found in surface waters. Approximately 1.14 grams of oxygen are required to oxidize one gram of nitrite nitrogen.

Nitrate nitrogen represents the completely oxidized form of nitrogen in the nitrogen cycle. Its major external sources in a watercourse are wastewater effluents and agricultural runoff. The nitrate form is quite soluble in water and concentrations can reach high levels, particularly since it does not adsorb on particulate matter and is chemically relatively nonreactive. In addition to the reduction of nitrate by heterotrophic bacteria at low DO levels (0-2 mg/l), it may also be used by phytoplankton as a nutrient source. The assimilated nitrate nitrogen is converted to organic nitrogen in the plant's cells. Upon death, the cellular material releases organic nitrogen which completes the nitrogen cycle.

From the standpoint of mathematical modeling the Potomac Estuary, there are two aspects of the nitrogen cycle that deserve special attention: (1) the reduction in dissolved oxygen by bacterial oxidation of unoxidized nitrogen forms (ammonia + organic nitrogen)* and (2) the assimilation of inorganic nitrogen forms by phytoplankton during their growth phase.

* Commonly measured as total Kjeldahl nitrogen

SIMPLIFIED NITROGEN CYCLE

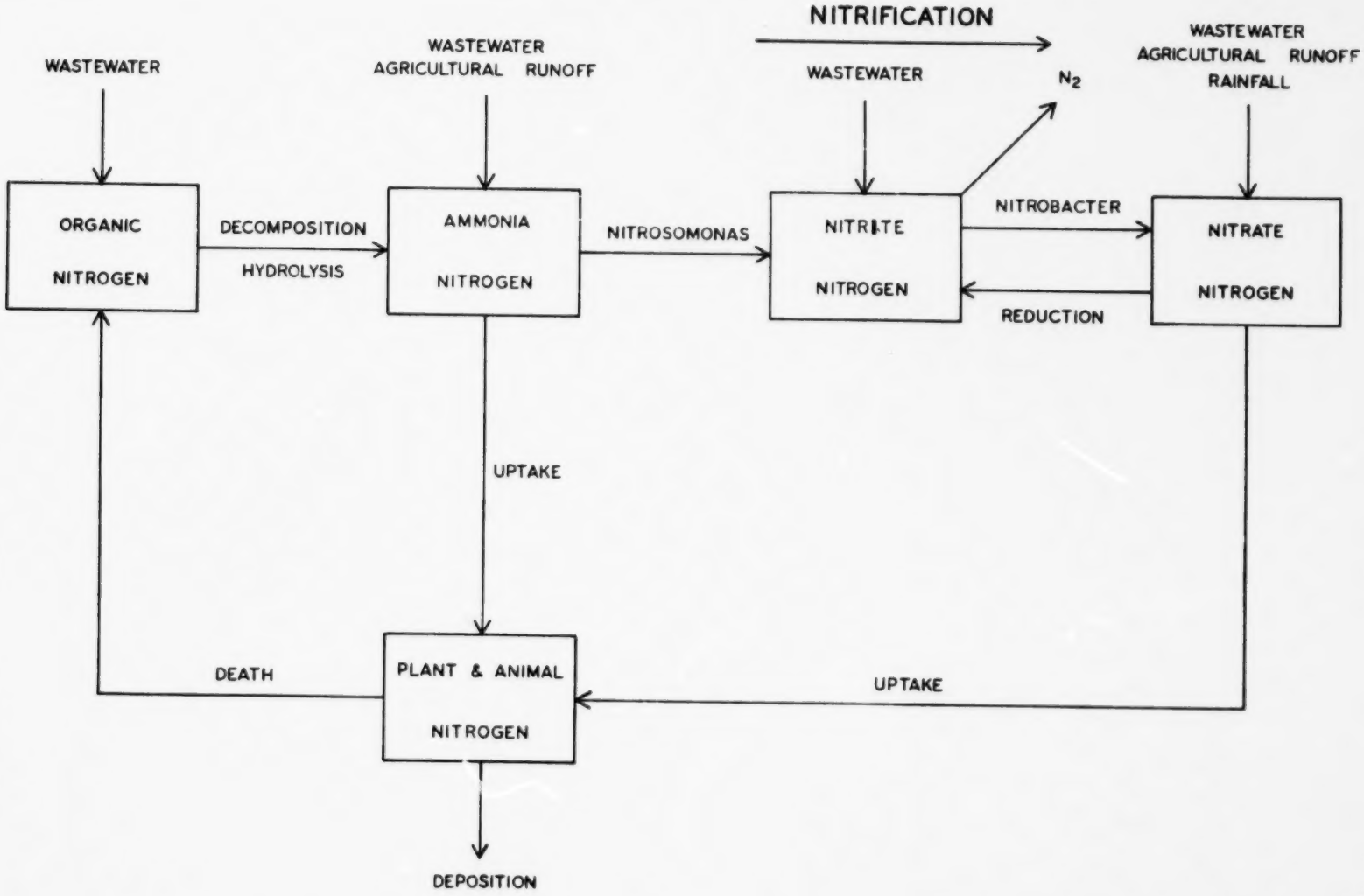


FIGURE V-1

2. Phosphorus

Since the advent of synthetic detergents, phosphorus levels in the natural environment have increased drastically and its role in the eutrophication process has received considerable attention. Shown in Figure V-2 is a schematic representation of a simplified phosphorus cycle with pertinent chemical, physical, and biological reactions. Although large quantities of mineral phosphates are present on the earth's surface, they are relatively insoluble in water.

Phosphorus in the aquatic environment can basically be categorized as either inorganic or organic. As shown in Figure V-2, inorganic phosphorus can be subdivided into: (1) particulate, (2) soluble ortho, and (3) soluble poly and pyro. The major contributor of soluble inorganic phosphorus is wastewater effluents. Prior to the inception of synthetic detergent use orthophosphate constituted most of the total phosphorus present in sewage, with the remainder being primarily dissolved and suspended organic compounds. Since that time, however, the cleansing agents polyphosphate and pyrophosphate have become predominant factors in water quality management. In addition to sewage sources, both inorganic and organic phosphorus (soluble and particulate) may be contributed in much smaller quantities by agricultural and other types of land runoff.

Polyphosphate and pyrophosphate are readily hydrolyzed to the orthophosphate form. Various sorption phenonmena can convert soluble orthophosphates to a particulate form or vice versa. Of the different

forms of inorganic phosphorus, only soluble orthophosphate can be biologically assimilated by phytoplankton. A portion of the particulate phosphorus is deposited in the bottom sediments. A quantitative appraisal of phosphorus recycling has not been undertaken, but it appears that the sediment adsorbs more phosphorus than it releases.

The organic phosphorus component also contains soluble and particulate phosphorus which undergo chemical and physical reactions similar to their inorganic counterparts. The oxidation of organic soluble phosphorus into an inorganic form is a relatively minor sink of DO. The cells of plants and animals convert inorganic phosphorus to an organic form; when these cells die, a certain portion is probably deposited. Biological decomposition of the remainder results in additional soluble and particulate organic phosphorus, and because of "luxury" uptake, some soluble inorganic phosphorus.

Phosphorus cycle factors of special concern in mathematical modeling studies are the gross deposition rate and the quantity biologically taken up by algae. While other aspects are also important, they are not as easily defined.

SIMPLIFIED PHOSPHORUS CYCLE

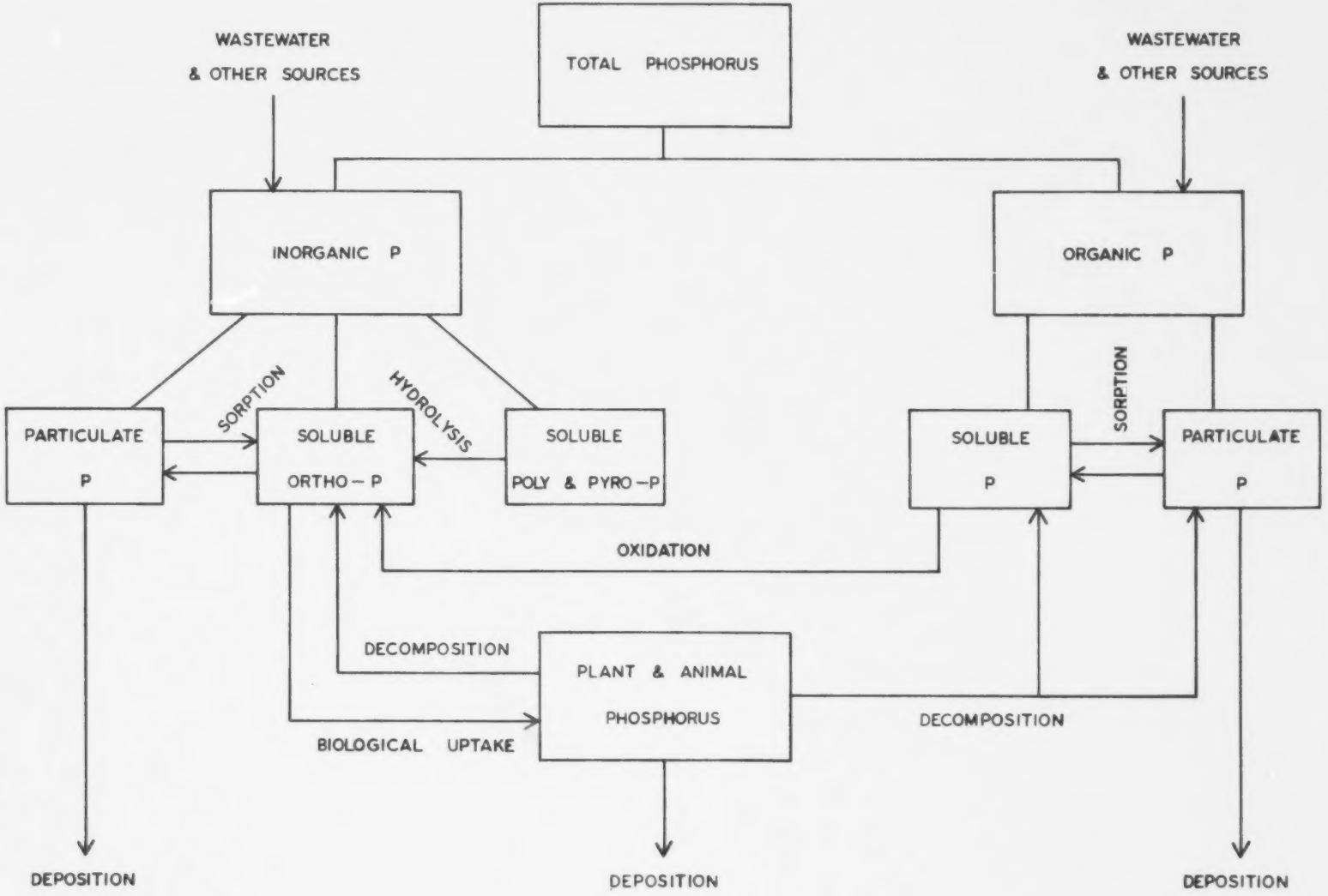


FIGURE V – 2

C. MATHEMATICAL MODELING TECHNIQUES

Water quality simulations discussed in this report were made using the EPA Dynamic Estuary Model (DEM) and DECS III (Thomann Model). Relatively steady-state conditions over a 2 or 3 week period were simulated with the DEM, whereas DECS III was used to simulate inter-seasonal conditions. The DEM is a real time system incorporating hydraulic and quality components. Both of these components utilize the same two-dimensional network of interconnecting junctions and channels. The hydraulic solution describes tidal movement, while the quality solution considers the basic transport mechanisms of advection and dispersion as well as the pertinent sources and sinks of each constituent. The DEM can concurrently simulate six different constituents. They may be either conservative or nonconservative and may be interrelated in any mathematical linkage. A detailed description of this model is available from EPA [2]. The application and verification of the DEM in simulating dye and chloride data in the Potomac Estuary and a detailed sensitivity analysis of the various input parameters have also been documented [4].

Several modifications were made to the DEM in order to simulate nutrient transport and historical dissolved oxygen distributions. A schematic diagram of the basic feedback linkage employed by the DEM to predict algal growth based on the nitrogen cycle and the effects of algae and other sources and sinks on the DO budget are shown in Figure V-3. One version of the DEM included five nitrogen reactions: (1) bacterial nitrification of ammonia to nitrite and nitrate, (2) phytoplankton utilization of inorganic nitrogen, (3) release of organic

nitrogen by the death of phytoplankton, (4) deposition of organic nitrogen, and (5) decomposition of organic nitrogen to ammonia. Moreover, the following DO budget linkages were included in a separate model: (1) oxidation of carbonaceous matter, (2) oxidation of nitrogenous matter (ammonia and organic), (3) oxygen production by photosynthesis and utilization by respiration of simulated algal standing crops based upon the nitrogen cycle, (4) benthic demand, and (5) reaeration from the atmosphere.

All model reactions were based on a mass balance basis. The mass conversion factors (nitrogen to chlorophyll a) were determined by algal composition analyses performed in the laboratory [5]. The rates used in the DO budget analysis were obtained primarily from field studies. Besides changing the various reaction rates temporally, a modification was made in the DO model to allow for spatial variations in the photosynthetic, respirational and benthic rates as well as the depth of the euphotic zone.

Simulations of phosphorus transport in the Potomac Estuary were based on second-order reaction kinetics. As will be discussed in a subsequent section of this report, adequate agreement between observed and predicted phosphorus profiles could not be obtained using a first-order system for deposition rates. Consequently, the DEM was modified to handle second and other order reactions. Linkage between algal growth and phosphorus loss in the model was performed similarly to that of the nitrogen cycle, e.g., mass balance analysis.

SIMPLIFIED DO BUDGET
FOR
DYNAMIC ESTUARY MODEL

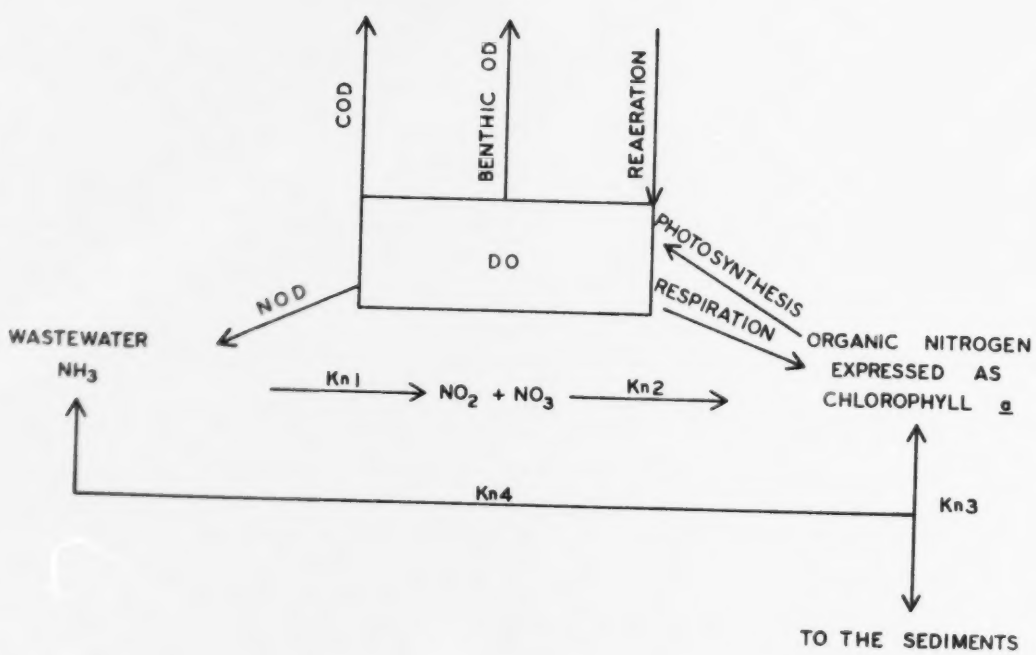


FIGURE V – 3

The DECS III model is based on a tidal average time-dependent solution of the basic mass balance equations as originally developed by Thomann [12]. These equations are expressed in finite difference form by segmenting the estuary under study. Since this model is nontidal, a dispersion coefficient is introduced to account for tidal dispersion and advection in addition to eddy and molecular diffusion. The quantitative appraisal of this coefficient becomes extremely difficult. AFO's experience in verifying DECS III for historical dye and chloride data and the estimation of dispersion coefficients for several reaches of the Potomac Estuary as a function of freshwater inflow is available in another report [4].

The major disadvantage of using DECS III is its limitation to a two-constituent linkage. Therefore, neither the complete nitrogen cycle nor the DO budget could be simulated. To help alleviate this problem, ammonia nitrogen and nitrate nitrogen replaced BOD and DO, respectively, in the original version of the model. The reaeration component sign was changed; it thus behaved as a sink of NO_3 instead of a source of DO. This loss would, of course, correspond to the biological uptake of NO_3 by algae. In such a manner, two nitrogen fractions could be properly represented.

Two other modifications were made to DECS III to permit the simulations given in this report: (1) the inclusion of second-order reaction kinetics for the analysis of phosphorus transport and (2) the inclusion of a mathematical expression relating dispersion coefficient

to freshwater flow. This latter addition was necessary since the simulation period was long in duration and was characterized by extreme flow differences.

CHAPTER VI

NITROGEN ASSIMILATION AND TRANSPORT

A. TEMPORAL AND SPATIAL DISTRIBUTION

The concentrations and forms of nitrogen in the Potomac Estuary are dependent upon wastewater loadings, temperature, freshwater inflow, and biological activity. The weekly nitrogen data collected by AFO from February 1969 to July 1970 are presented in isopleth form in Figure VI-1 (Ammonia Nitrogen), VI-2 (Nitrite + Nitrate Nitrogen), and VI-3 (Organic Nitrogen).

As shown in Figure VI-1, ammonia concentrations of 2.0 mg/l were fairly common in the upper estuary in 1969 as a result of wastewater discharges. The rapid decrease in concentrations between the Woodrow Wilson Bridge (River Mile 12) and Indian Head (River Mile 31) is indicative of nitrification or the conversion of ammonia nitrogen to nitrite and nitrate nitrogen. Based upon the data shown in Figure VI-1, the rate of this reaction appears to be definitely related to temperature.

During the warm summer months, for example, ammonia concentrations in the vicinity of Dogue Creek (River Mile 22) were about 0.5 mg/l, whereas concentrations during winter and spring periods averaged 1.0 - 1.5 mg/l. The almost immediate effects of nitrification would indicate that the upper Potomac Estuary behaves as a "continuous-culture system." It should also be noted that changes in freshwater flow rates had a

relatively minor effect on the ammonia nitrogen levels upstream from Hains Point (River Mile 7.6).

The concentrations of nitrite and nitrate nitrogen at any given time will be a function of (1) nitrification rate and (2) nitrate uptake by algal cells. Figure VI-2 shows maximum nitrite and nitrate nitrogen concentrations (1.5 - 2.0 mg/l) throughout much of the summer and fall of 1969 and again in January 1970. These high levels generally prevailed between Woodrow Wilson Bridge and Indian Head where rapid reduction in ammonia levels was observed. Besides the conversion of ammonia from wastewater effluents, a considerable amount of nitrate nitrogen enters the upper Potomac Estuary during periods of high freshwater flow. This contribution would account for the high concentrations in January 1970, a low-temperature, minimal nitrification period.

The significant decrease in nitrite and nitrate nitrogen between Indian Head and Smith Point (River Mile 46) in the summer and early fall of 1969 was caused by algal uptake of nitrogen. This reaction, like nitrification, appears to be related to temperature as evidenced by the greater persistence of nitrate nitrogen during colder periods.

From a water quality management standpoint, the virtual disappearance of inorganic nitrogen in the critical algal growing areas suggests that this nutrient may become the major factor in limiting algal growth in the middle reach of the Potomac Estuary.

The distribution of organic nitrogen in the Potomac Estuary during 1969-70 is shown in Figure VI-3. These iso-concentration lines were

based on differencing the total Kjeldahl nitrogen (TKN) and ammonia nitrogen data. As shown in Figure VI-3, organic nitrogen is quite plentiful in the Potomac Estuary, especially during the late summer and early fall of 1969. Maximum concentrations, exceeding 3.0 mg/l, were observed in the middle estuary throughout most of September 1969 with the lower reach having levels nearer 2.0 mg/l. These extremenly high levels of organic nitrogen resulted from the profuse algal blooms which were visually observed and measured at greater than 100 µg/l chlorophyll a. The maximum recorded chlorophyll value during this critical period was 445 µg/l. Algal composition studies conducted by AFO [5] indicate that water with an algal bloom of 100 µg/l chlorophyll a contains about 1.0 mg/l of organic nitrogen.

Relatively high organic nitrogen concentrations (1.5 - 2.0 mg/l) continued in the upper and middle estuary through October 1969. Similar concentrations were again observed in June and July 1970 when a reappearance of algal blooms occurred.

It would appear from a comparison of the ammonia nitrogen and organic nitrogen data that the rate of decomposition of organic nitrogen is much slower than the rate of bacterial nitrification, since organic nitrogen is the predominant form of nitrogen in the middle and lower estuary.

AMMONIA NITROGEN ISOPLETH

POTOMAC ESTUARY

1969 - 1970 DATA

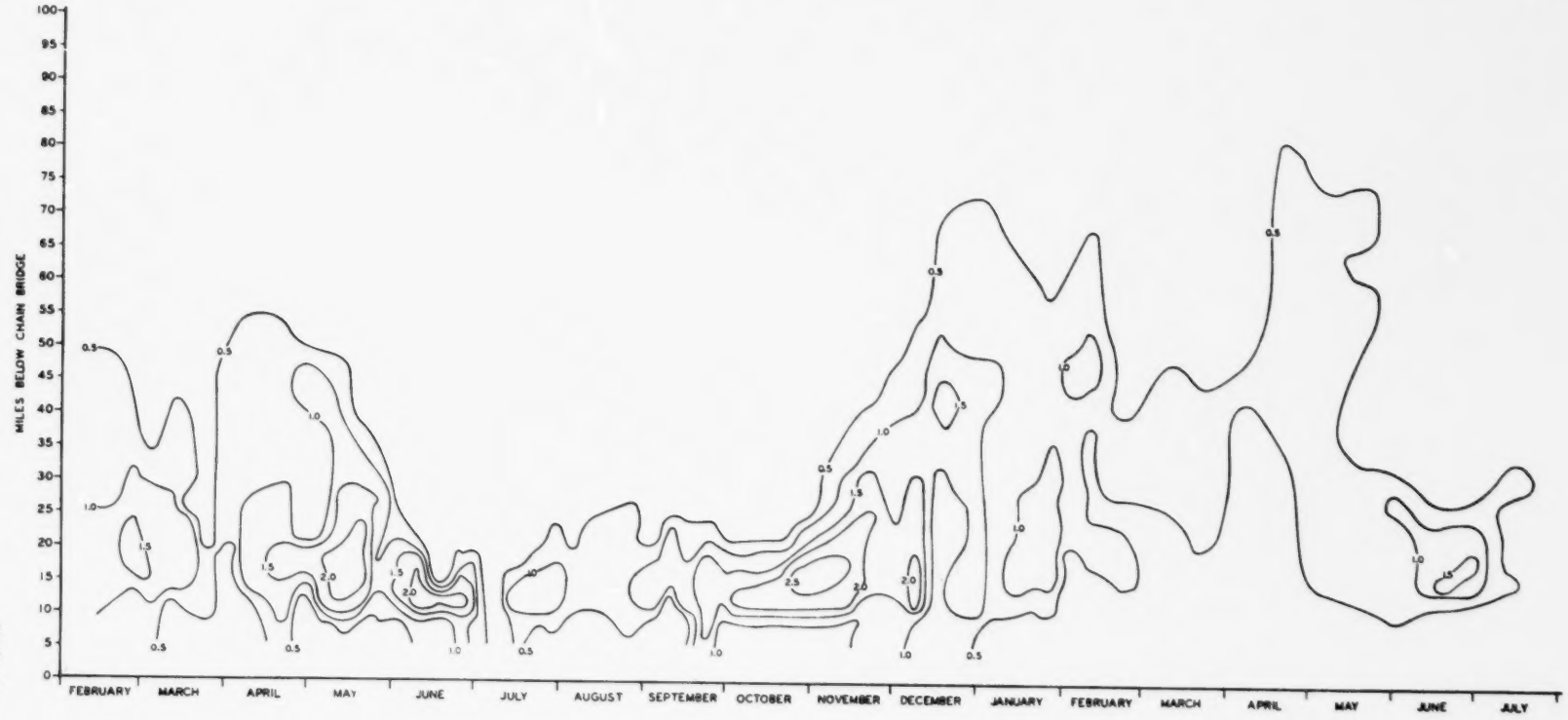


FIGURE VA-1

NITRITE + NITRATE NITROGEN ISOPLETH

POTOMAC ESTUARY

1969-1970 DATA

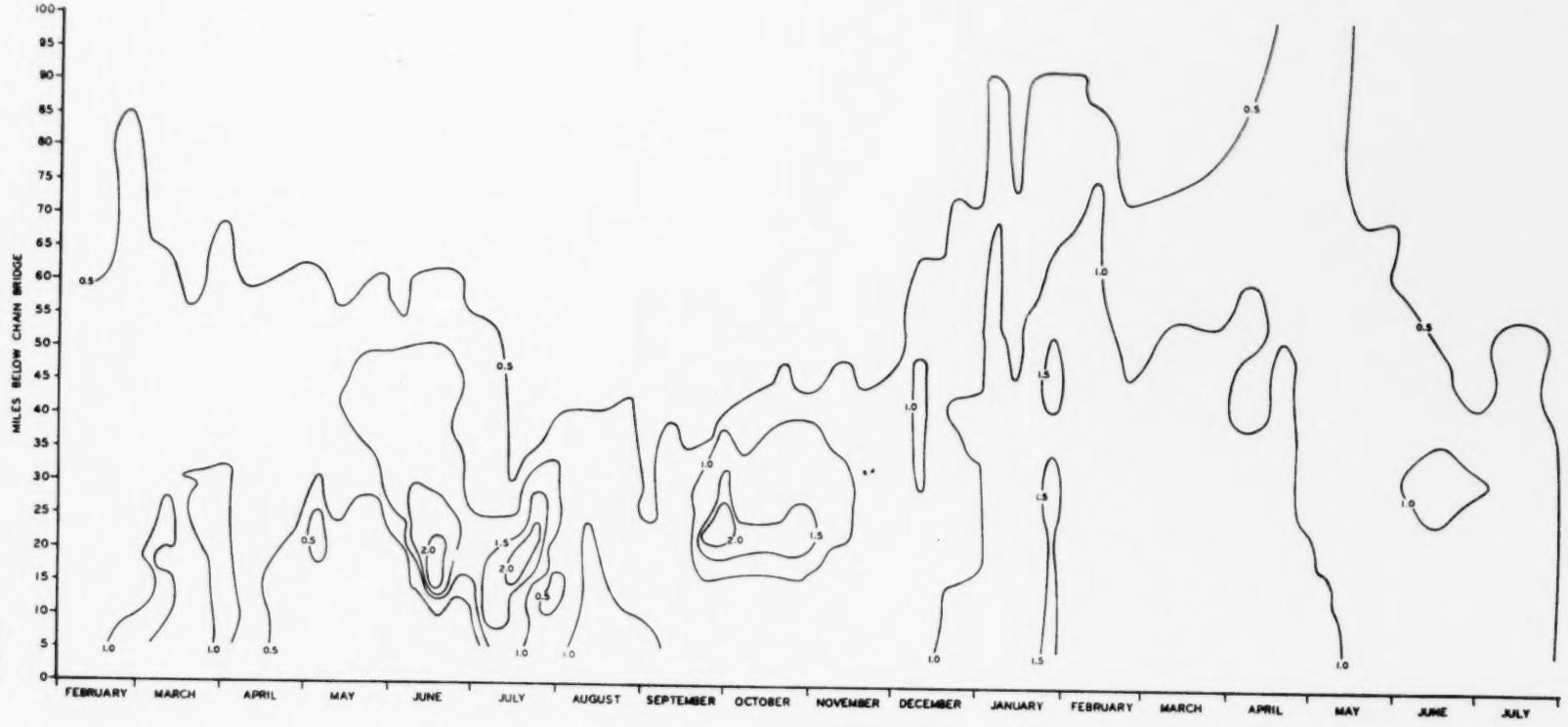


FIGURE VI-2

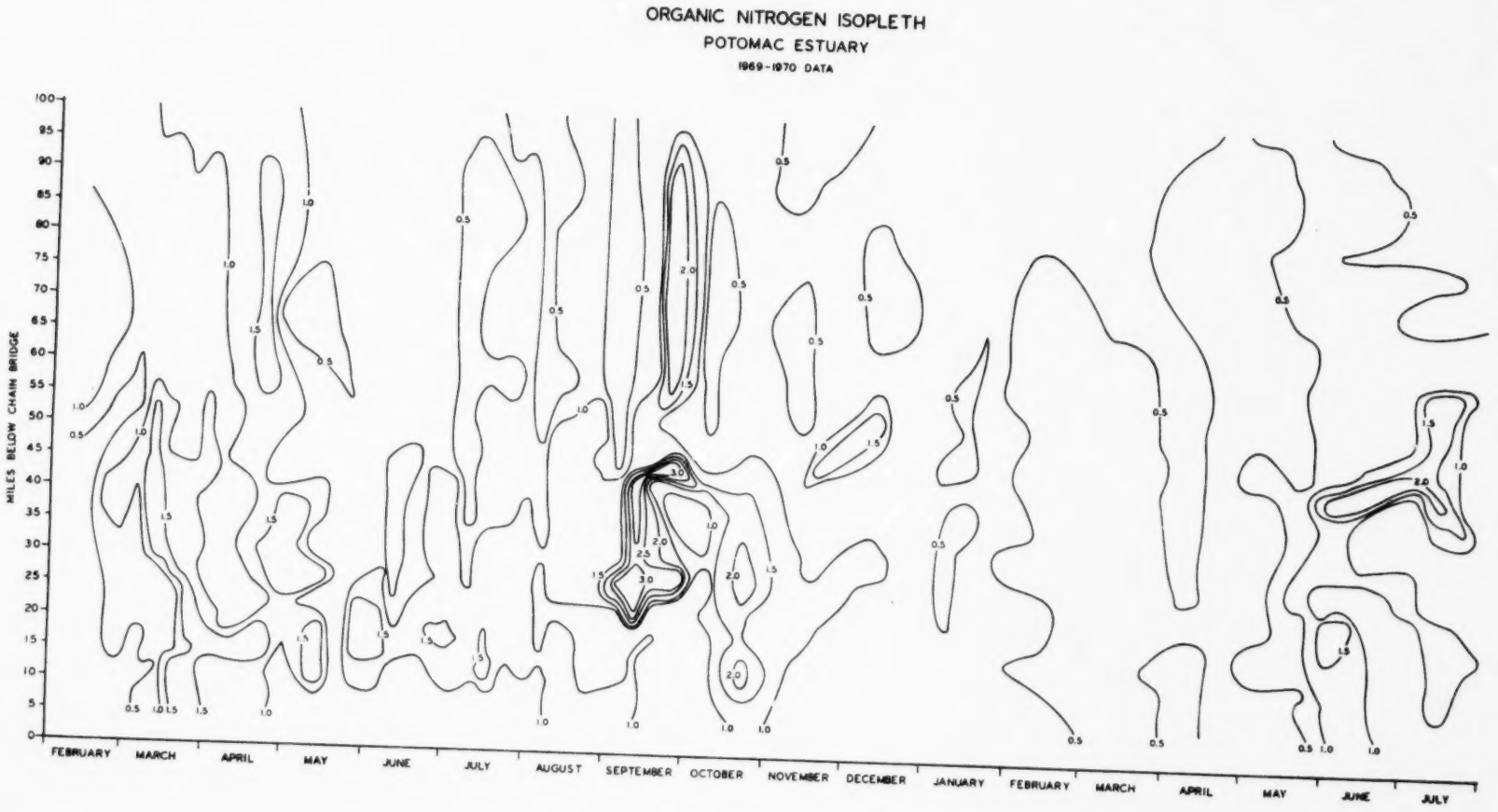

ORGANIC NITROGEN ISOPLETH
POTOMAC ESTUARY
1969-1970 DATA
MILES BELOW CHAIN BRIDGE
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY

FIGURE VI-3

B. DETERMINATION OF REACTION RATES AND TEMPERATURE EFFECTS

1. Nitrification

The rate at which ammonia nitrogen (NH_3) is biochemically oxidized to nitrite and nitrate nitrogen ($NO_2 + NO_3$), commonly referred to as the nitrification rate, was determined for the Potomac Estuary by using the aforementioned version of DEM to simulate numerous observed conditions representing a variety of temperatures and freshwater inflows. The prototype behavior was established using intensive-type sampling data collected during relatively steady-state flow periods. These data indicated that ammonia was being rapidly depleted, especially when high temperatures prevailed, and that a subsequent increase in nitrate concentrations could be expected. Because of this and the fact that maximum depletion occurred upstream from the major algal blooms, it was apparent that nitrification, and not biological uptake by phytoplankton, was primarily responsible for the loss of ammonia.

Various reaction rates were inputted to the Dynamic Estuary Model until a reasonable simulation of each of the observed ammonia profiles was achieved. The final profiles obtained with the model along with the appropriate nitrification rates are shown in Figures VI-4 through VI-16. As can be seen in the figures, peak ammonia concentrations and spatial gradients were generally simulated satisfactorily.

In order to establish a relationship between nitrification rate and temperature, a regression analysis was performed utilizing the thirteen separate sets of data discussed above. The linear relationship

resulting from this analysis is presented in Figure VI-17. At 20°C, the nitrification rate is 0.084/day (base e).

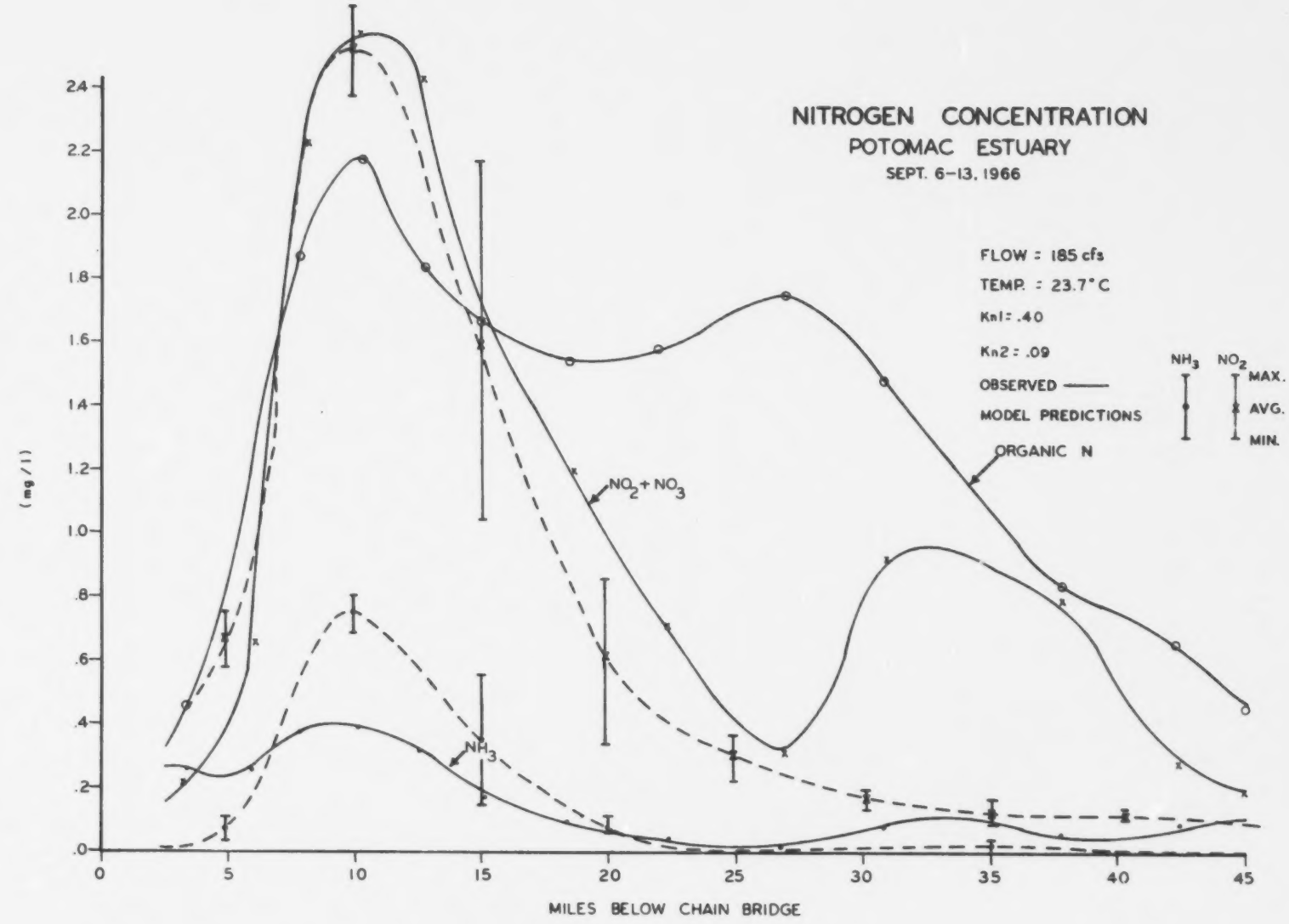

NITROGEN CONCENTRATION
POTOMAC ESTUARY
SEPT. 6-13, 1966
FLOW = 185 cfs
TEMP. = 23.7°C
Kn1 = .40
Kn2 = .09
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
ORGANIC N
NO2 + NO3
NH3
(mg/l)
MILES BELOW CHAIN BRIDGE
0
5
10
15
20
25
30
35
40
45
.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

FIGURE VI-4

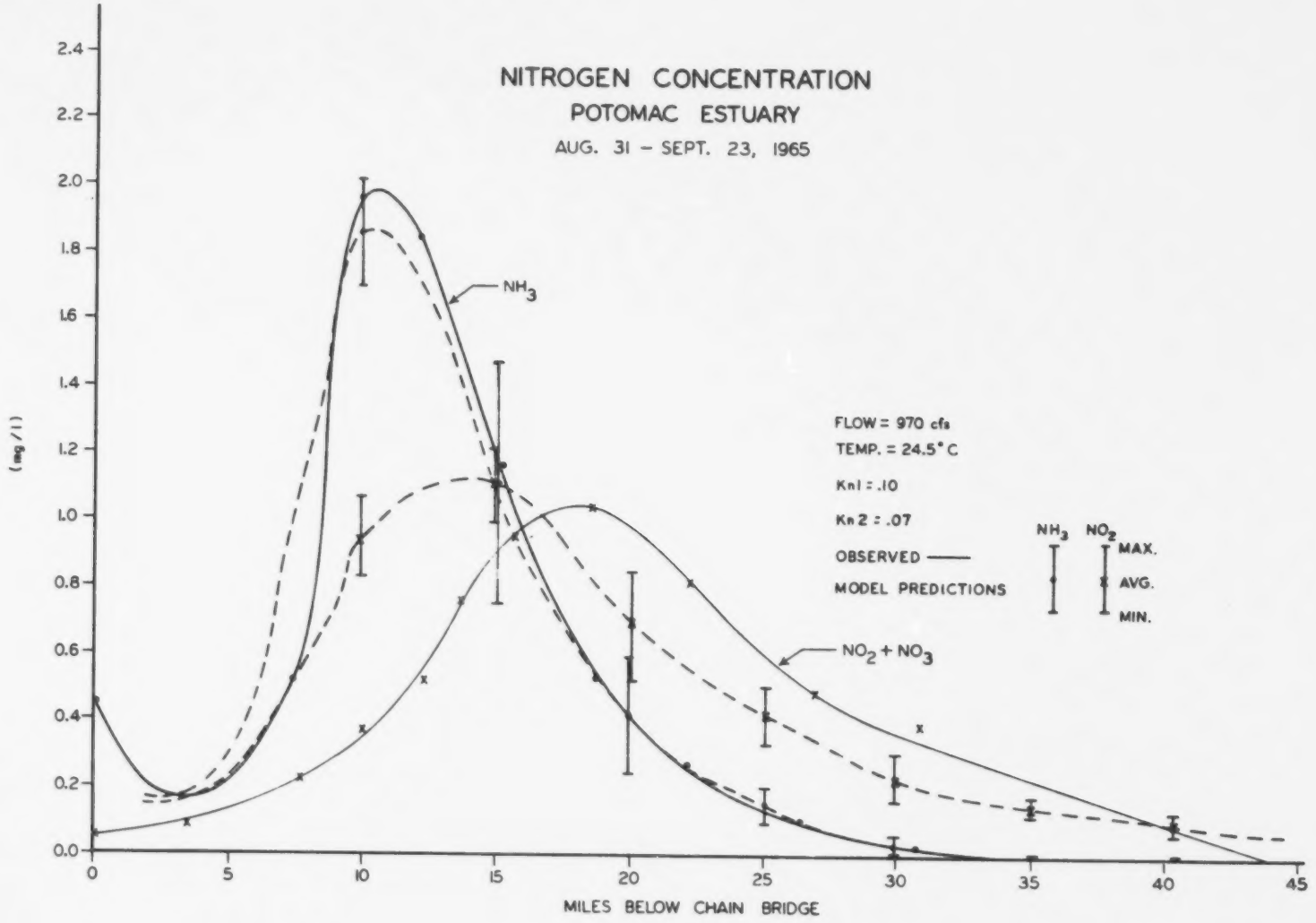

NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUG. 31 – SEPT. 23, 1965
(mg/l)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
NH3
NO2 + NO3
FLOW = 970 cfs
TEMP. = 24.5° C
Kn1 = .10
Kn2 = .07
OBSERVED ——
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-5

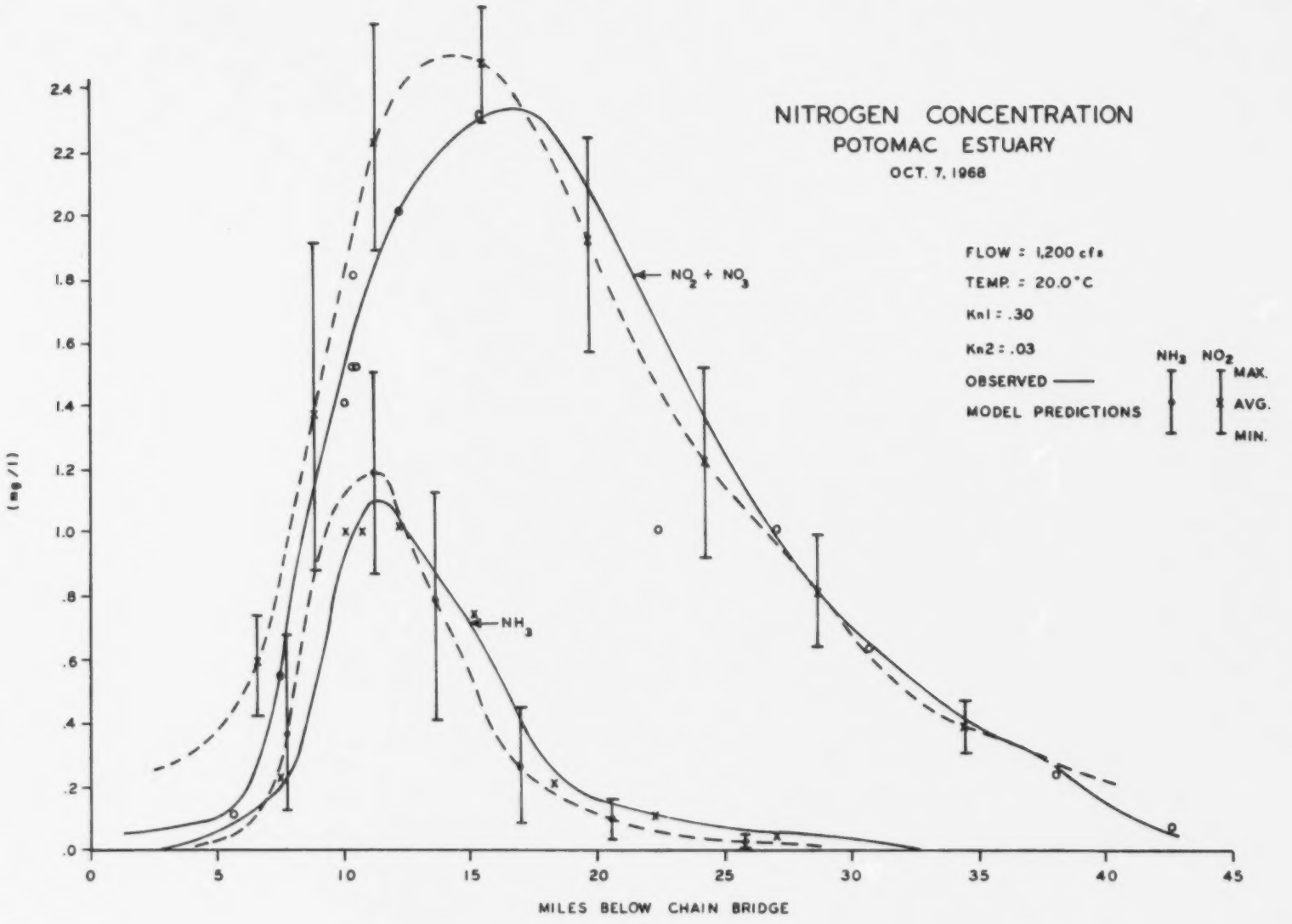

NITROGEN CONCENTRATION
POTOMAC ESTUARY
OCT. 7, 1968
FLOW = 1,200 cfs
TEMP. = 20.0°C
Kn1 = .30
Kn2 = .03
OBSERVED ——
MODEL PREDICTIONS
NH3 NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
(mg/l)
MILES BELOW CHAIN BRIDGE
0
5
10
15
20
25
30
35
40
45
.0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

FIGURE VI-6

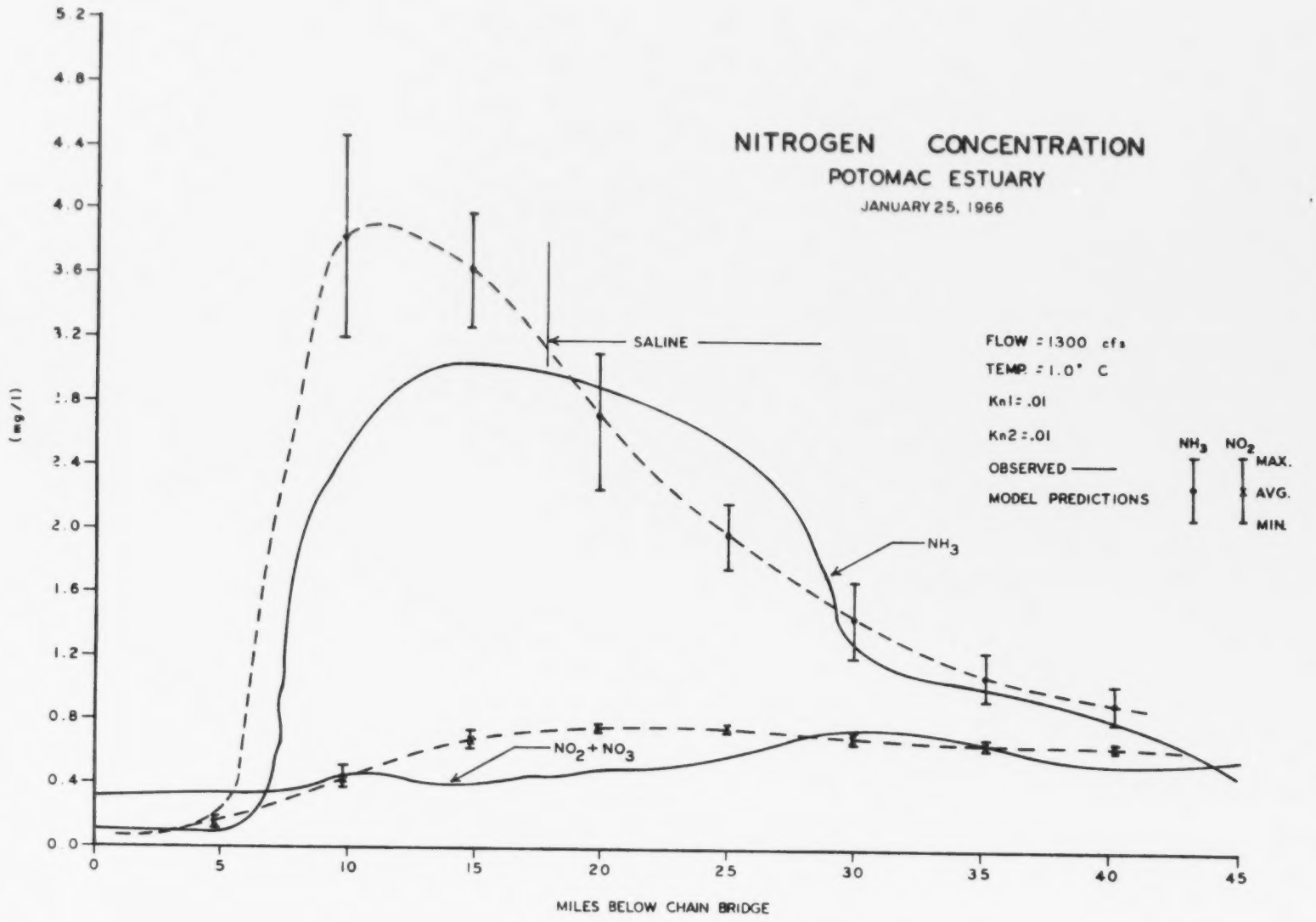

NITROGEN CONCENTRATION
POTOMAC ESTUARY
JANUARY 25, 1966
FLOW = 1300 cfs
TEMP. = 1.0° C
Kn1 = .01
Kn2 = .01
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
SALINE
NH3
NO2 + NO3
(mg/l)
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-7

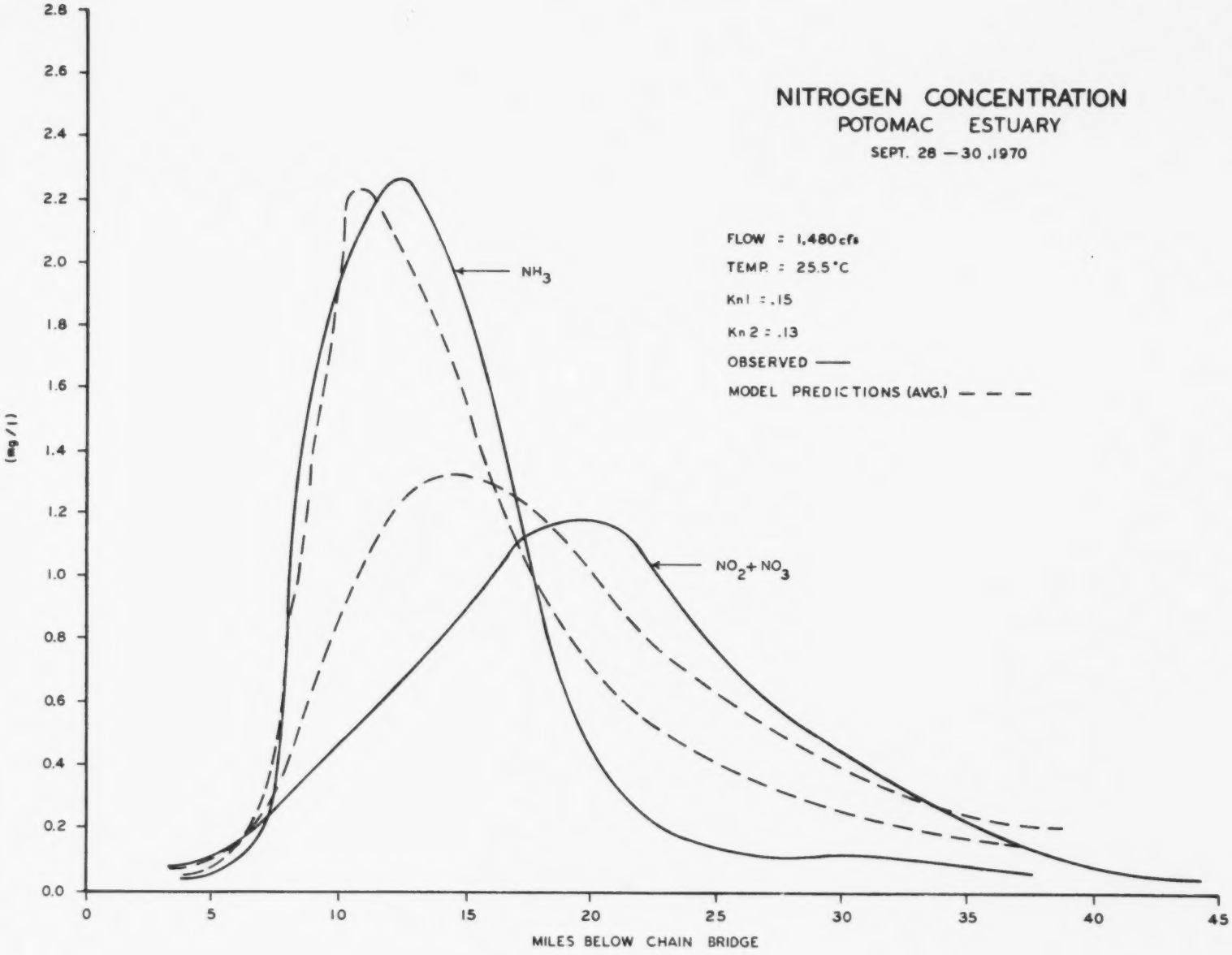

NITROGEN CONCENTRATION
POTOMAC ESTUARY
SEPT. 28 — 30 ,1970
FLOW = 1,480 cfs
TEMP. = 25.5 °C
Kn1 = .15
Kn2 = .13
OBSERVED ——
MODEL PREDICTIONS (AVG.) — — —
NH3
NO2+NO3
(mg/l)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-8

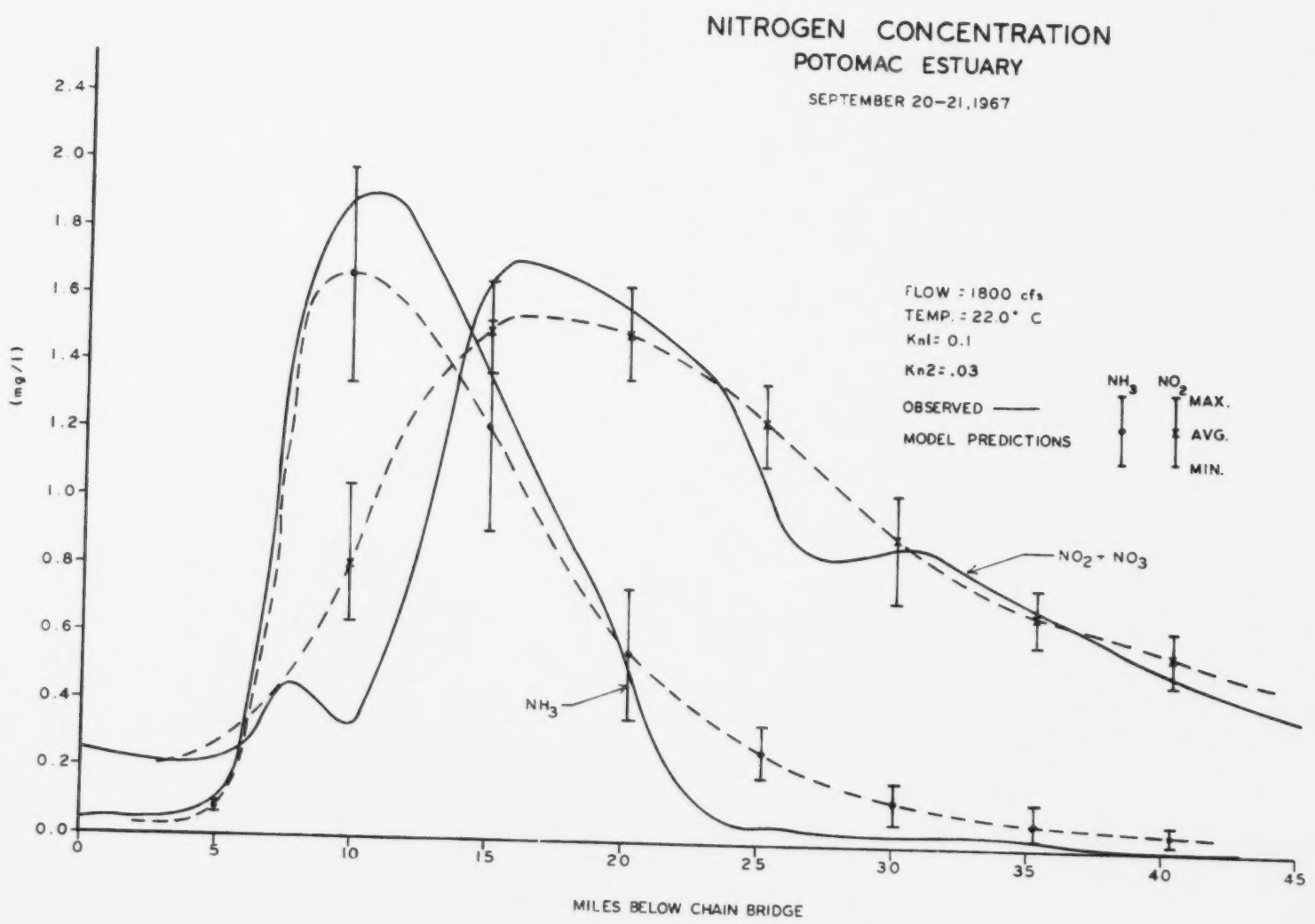

NITROGEN CONCENTRATION
POTOMAC ESTUARY
SEPTEMBER 20-21, 1967
FLOW = 1800 cfs
TEMP. = 22.0° C
Kn1 = 0.1
Kn2 = .03
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
(mg/l)
2.4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-9

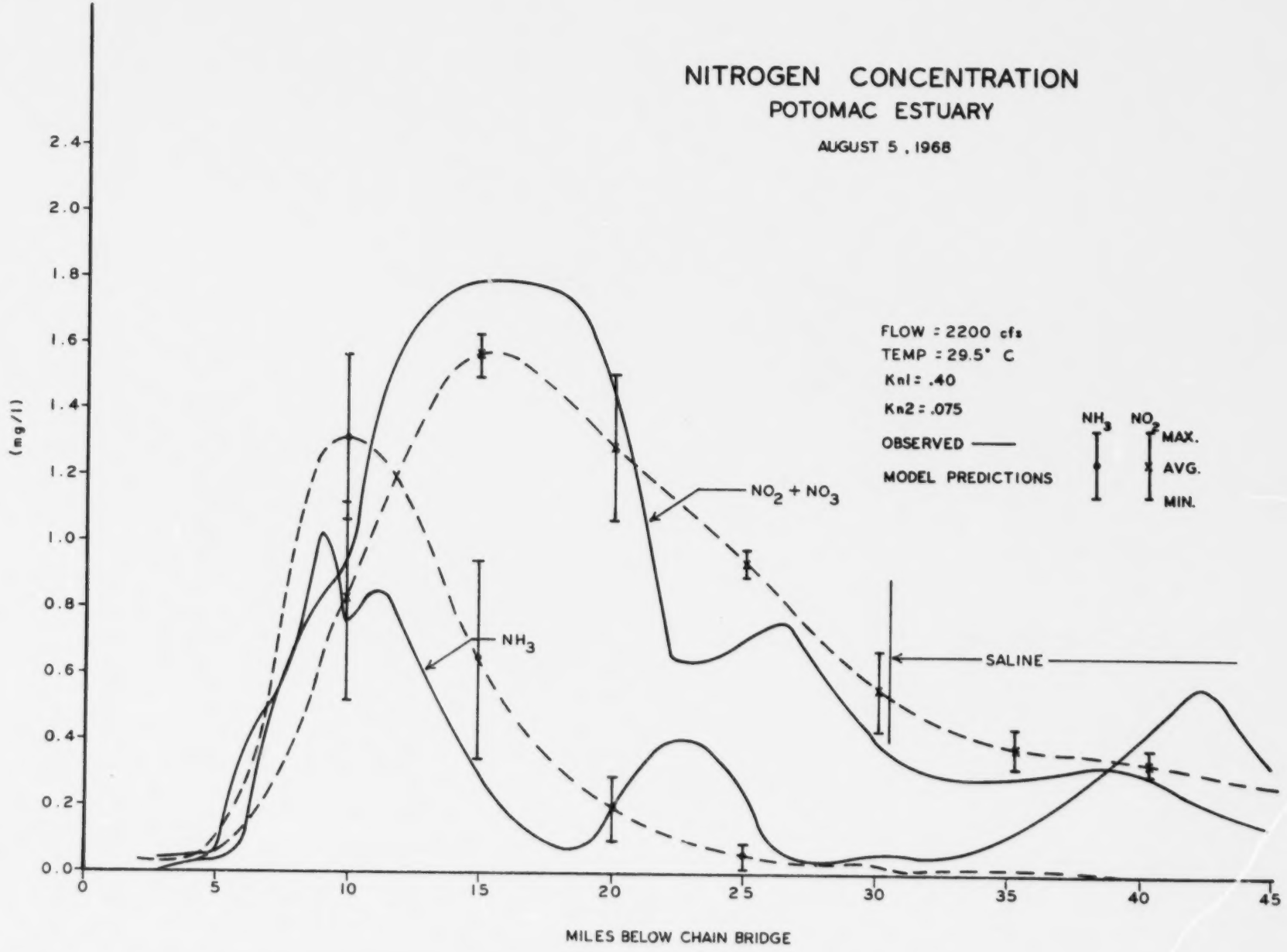

NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUGUST 5, 1968
FLOW = 2200 cfs
TEMP = 29.5° C
Kn1 = .40
Kn2 = .075
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
SALINE
(mg/l)
2.4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-10

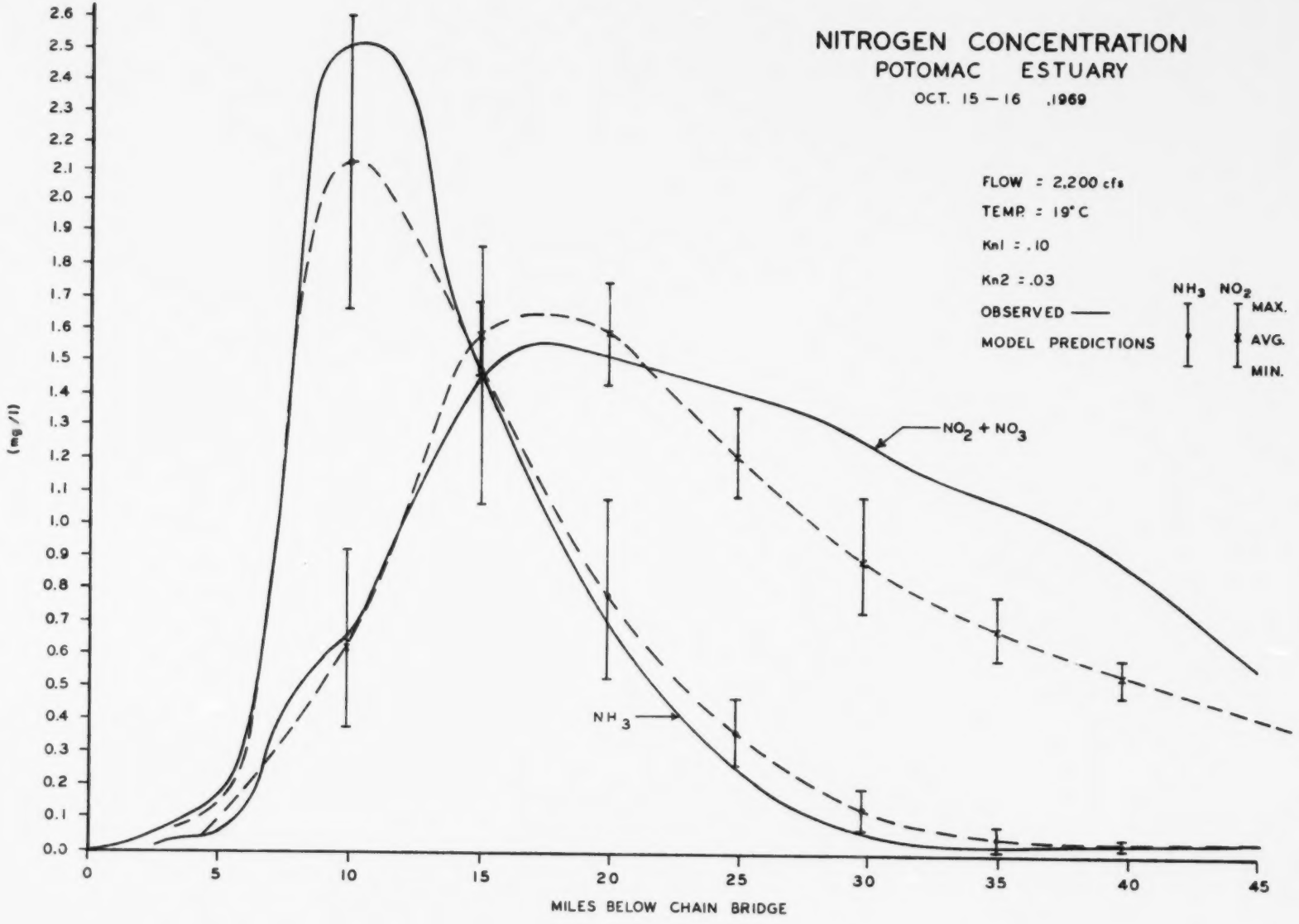

NITROGEN CONCENTRATION
POTOMAC ESTUARY
OCT. 15 – 16 ,1969
FLOW = 2,200 cfs
TEMP. = 19°C
Kn1 = .10
Kn2 = .03
OBSERVED ——
MODEL PREDICTIONS
NH3 NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
(mg/l)
MILES BELOW CHAIN BRIDGE
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6
0 5 10 15 20 25 30 35 40 45

FIGURE VI-11

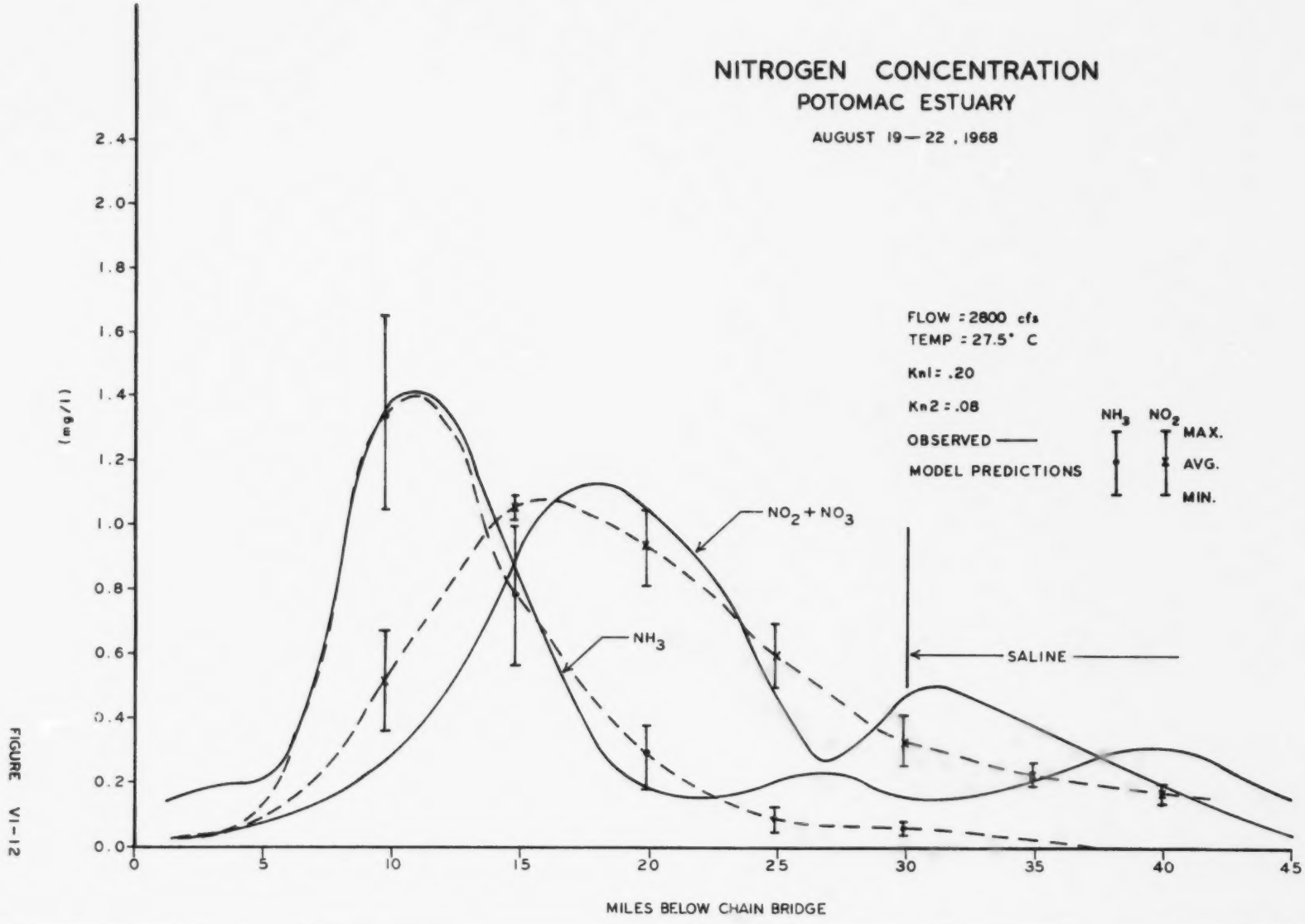

NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUGUST 19—22, 1968
FLOW = 2800 cfs
TEMP = 27.5° C
Kn1 = .20
Kn2 = .08
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
SALINE
(mg/l)
2.4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-12

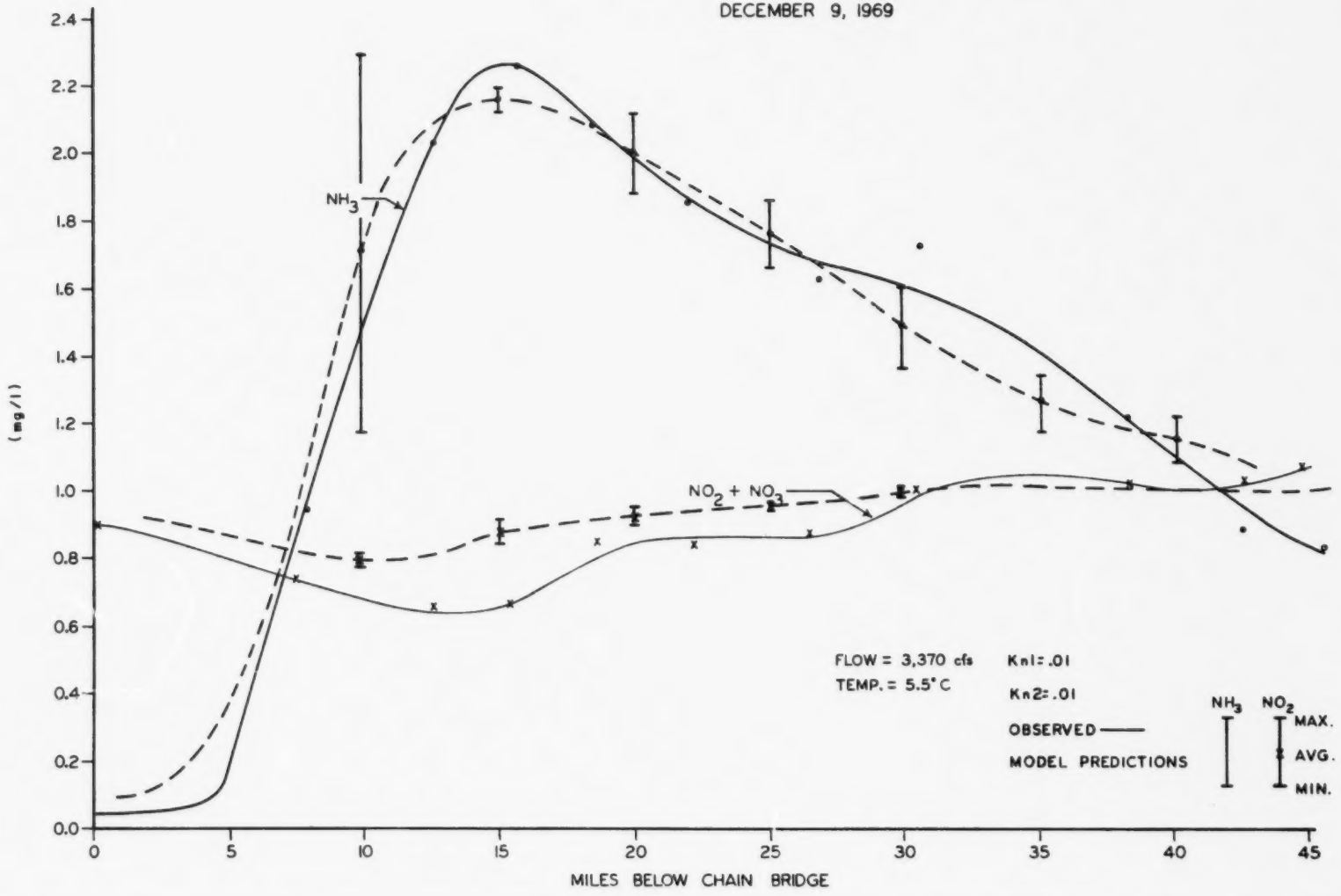

NITROGEN CONCENTRATION
POTOMAC ESTUARY
DECEMBER 9, 1969
(mg/l)
NH3
NO2 + NO3
FLOW = 3,370 cfs
TEMP. = 5.5°C
Kn1=.01
Kn2=.01
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
MILES BELOW CHAIN BRIDGE

FIGURE VI-13

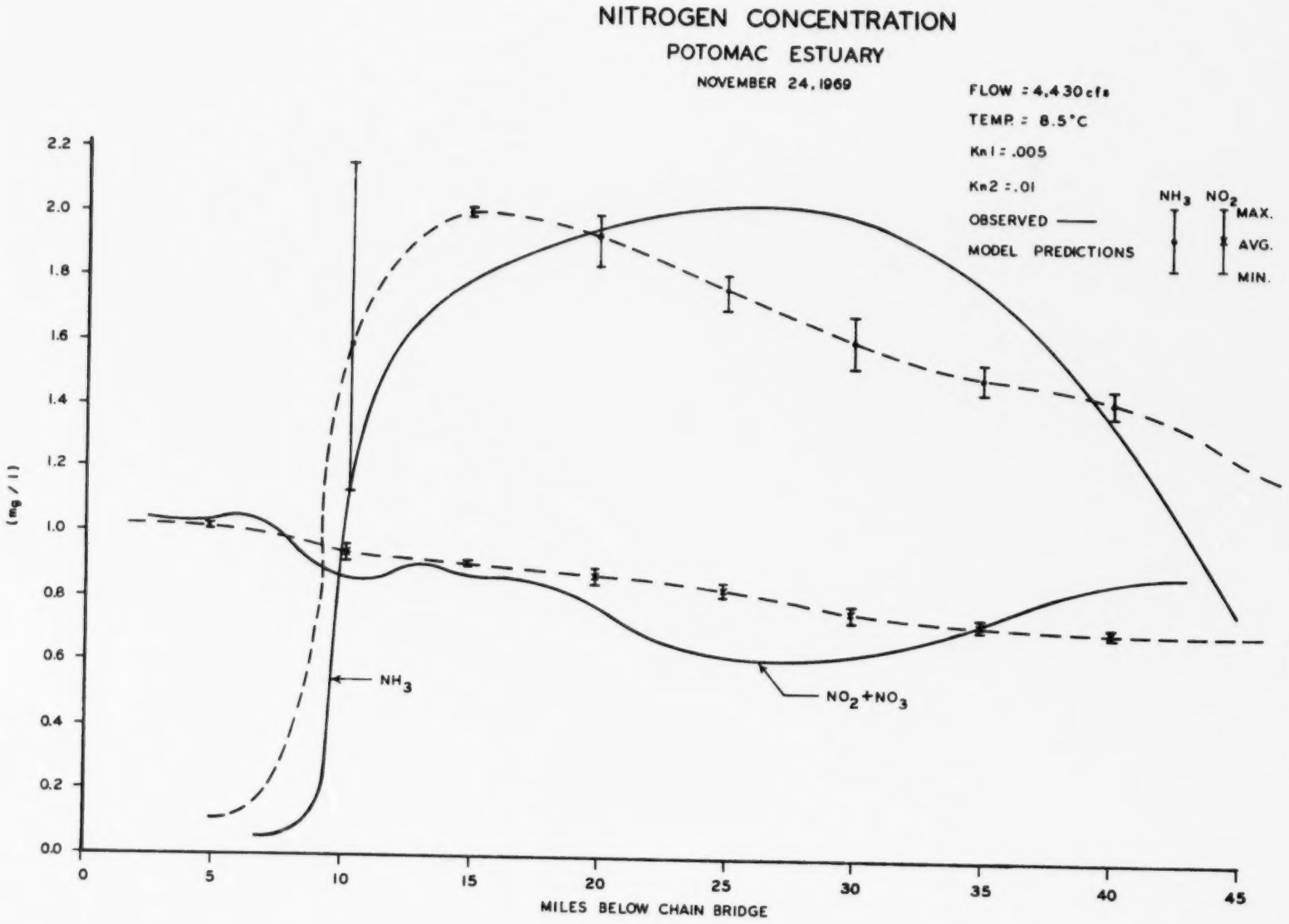

NITROGEN CONCENTRATION
POTOMAC ESTUARY
NOVEMBER 24, 1969
FLOW = 4,430 cfs
TEMP. = 8.5°C
Kn1 = .005
Kn2 = .01
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
(mg / l)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
NH3
NO2+NO3
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-14

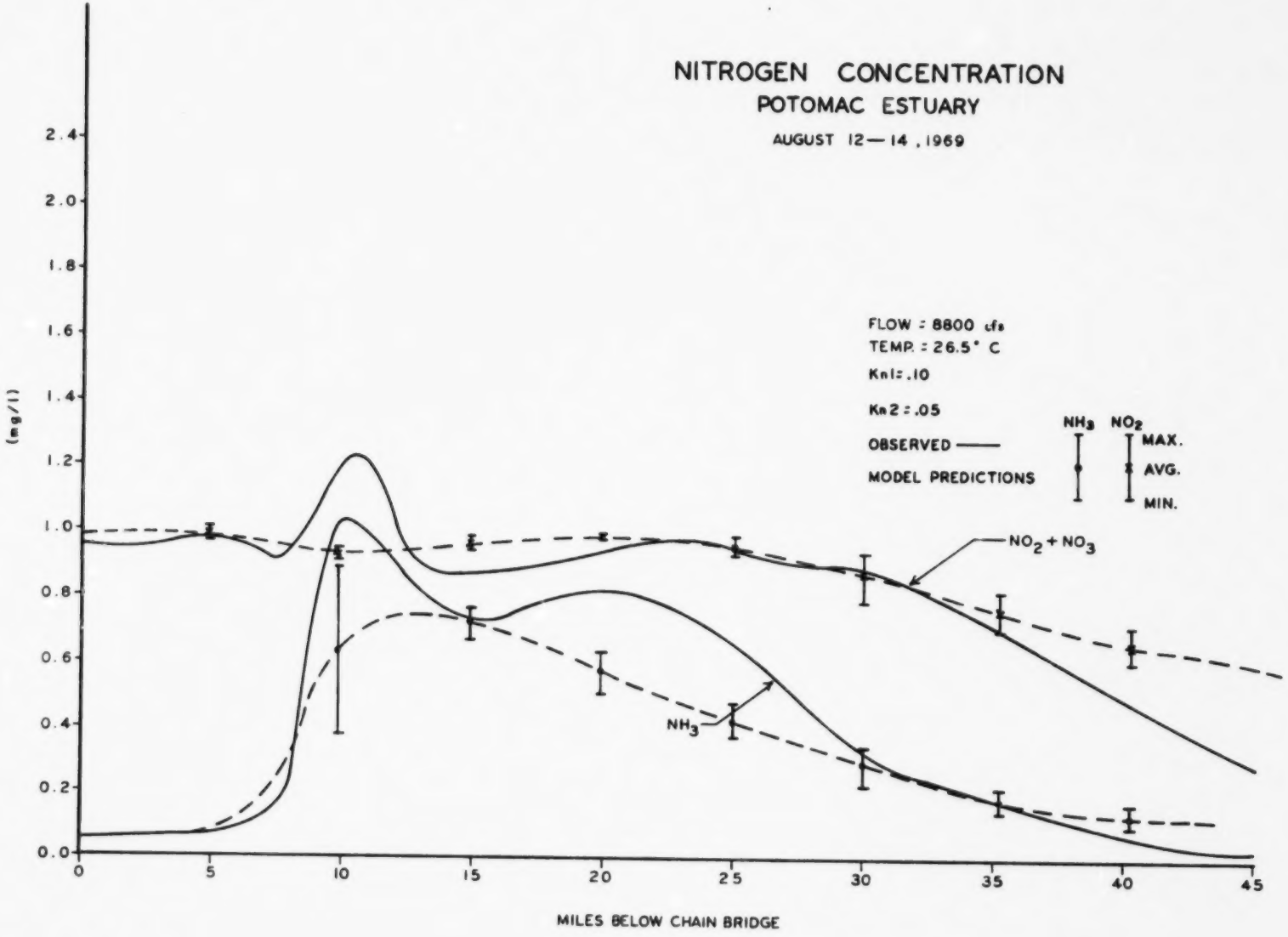

NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUGUST 12—14, 1969
FLOW = 8800 cfs
TEMP. = 26.5° C
Kn1=.10
Kn2 = .05
OBSERVED
MODEL PREDICTIONS
NH3
NO2
MAX.
AVG.
MIN.
NO2 + NO3
NH3
(mg/l)
2.4
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-15

NITROGEN CONCENTRATION
POTOMAC ESTUARY
APRIL 21, 1966

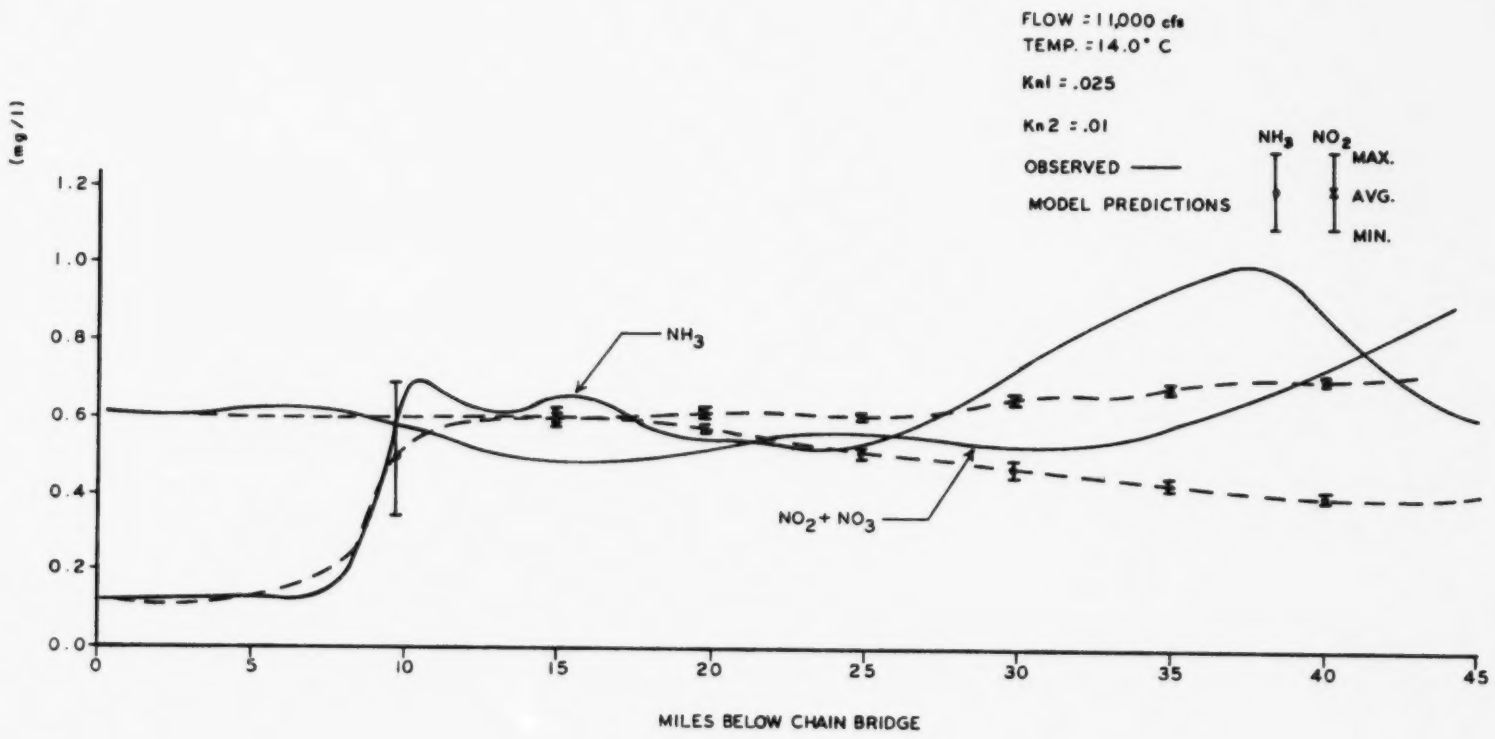


FIGURE VI-16

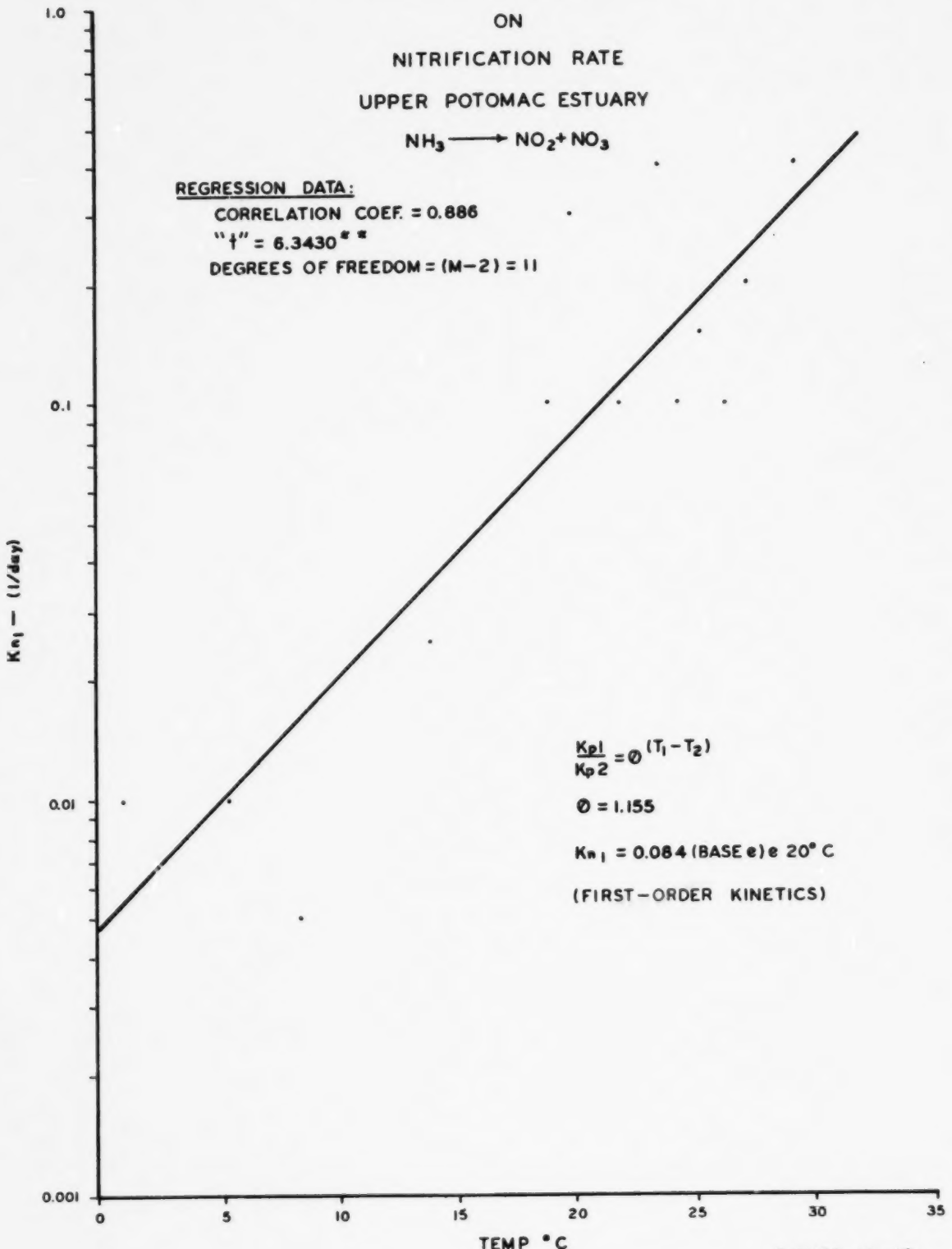
EFFECT OF TEMPERATURE

ON

NITRIFICATION RATE

UPPER POTOMAC ESTUARY

$NH_3 \longrightarrow NO_2 + NO_3$



REGRESSION DATA:

CORRELATION COEF. = 0.886

"t" = 6.3430 * *

DEGREES OF FREEDOM = (M−2) = 11

$\frac{K_{p1}}{K_{p2}} = \emptyset^{(T_1 - T_2)}$

$\emptyset = 1.155$

K_{n1} = 0.084 (BASE e) @ 20° C

(FIRST-ORDER KINETICS)

FIGURE VI-17

2. Algal Uptake

The predicted formation of nitrate nitrogen by the nitrification process was found to be quite high when compared with actual sampling data. It was, therefore, necessary to apply a decay mechanism to account for the nitrate uptake by phytoplankton and effect a better comparison. The appropriate reaction rates were determined utilizing the mathematical model and a trial and error approach similar to the one described for nitrification in the preceding section.

Figures VI-4 through VI-16 show observed and predicted nitrate profiles for the upper Potomac Estuary at different temperature and flow conditions. Also shown are the algal uptake rates used in the model. The figures indicate that reasonable agreement between prototype and model data was obtained.

The effect of temperature on the rates of algal nitrogen utilization is presented in Figure VI-18. A regression analysis was performed on the data and the results are statistically valid. At 20°C, the rate of nitrogen uptake by algae is 0.037/day (base e).

EFFECT OF TEMPERATURE

ON

ALGAL NITROGEN UTILIZATION RATE

UPPER POTOMAC ESTUARY

$NO_3 \longrightarrow$ ALGAL NITROGEN

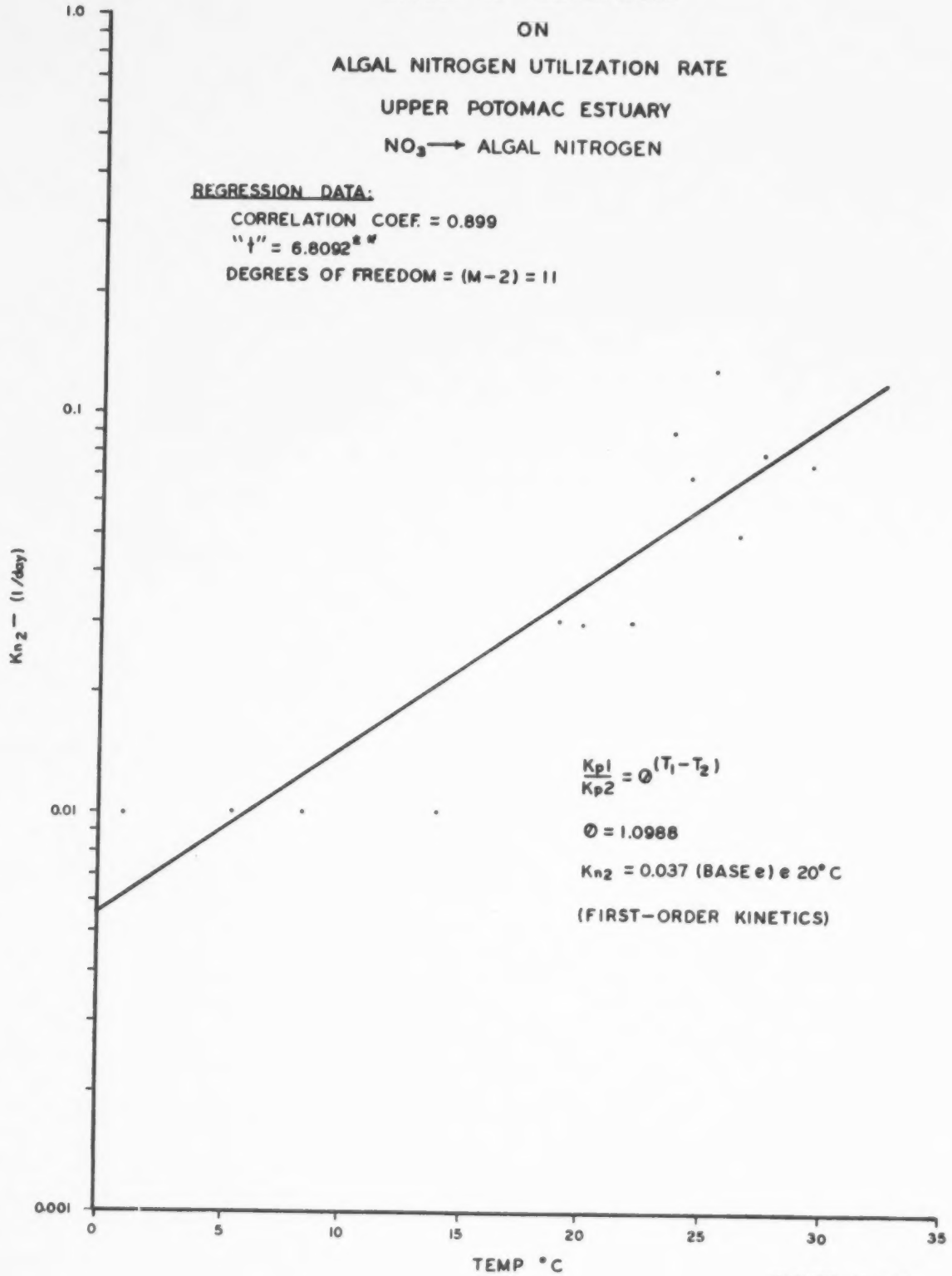


FIGURE VI-18

C. SIMULATION OF NITROGEN TRANSPORT THROUGH AN ANNUAL CYCLE

The two primary reactions involving nitrogen, i.e. nitrification and algal uptake of inorganic nitrogen, were incorporated in the DECS III version of the Thomann Model to simulate nitrogen transport in the Potomac Estuary throughout an annual cycle. Observed data collected weekly from February 1969 to July 1970 was used for comparison purposes and model verification.

The reaction rates and temperature effects developed from the preceding nitrogen verification runs were used in the model with certain modifications. These modifications generally consisted of reducing the nitrification rates to reflect (1) low DO concentrations and (2) high freshwater inflows. The former would inhibit biological oxidation by the aerobic nitrifying bacteria and the latter would cause a flushing action resulting in a lag time for repopulation of the nitrifiers which must be anticipated. In the case of biological uptake rates, a downward attenuation was performed when and where algal standing crop levels were believed to be abnormally low.

Observed and predicted nitrogen profiles (both ammonia and nitrate nitrogen) are presented in Figures VI-19 to VI-23 for five different sampling stations in the Potomac Estuary. An examination of the data indicates that the basic seasonal and spatial distributions were simulated surprisingly well. In view of limitations in observed data and simplification in the model itself, a closer agreement, especially in short-term fluctuations, was not really expected.

ANNUAL NITROGEN PROFILES
POTOMAC ESTUARY AT HAINS POINT
1969 - 1970

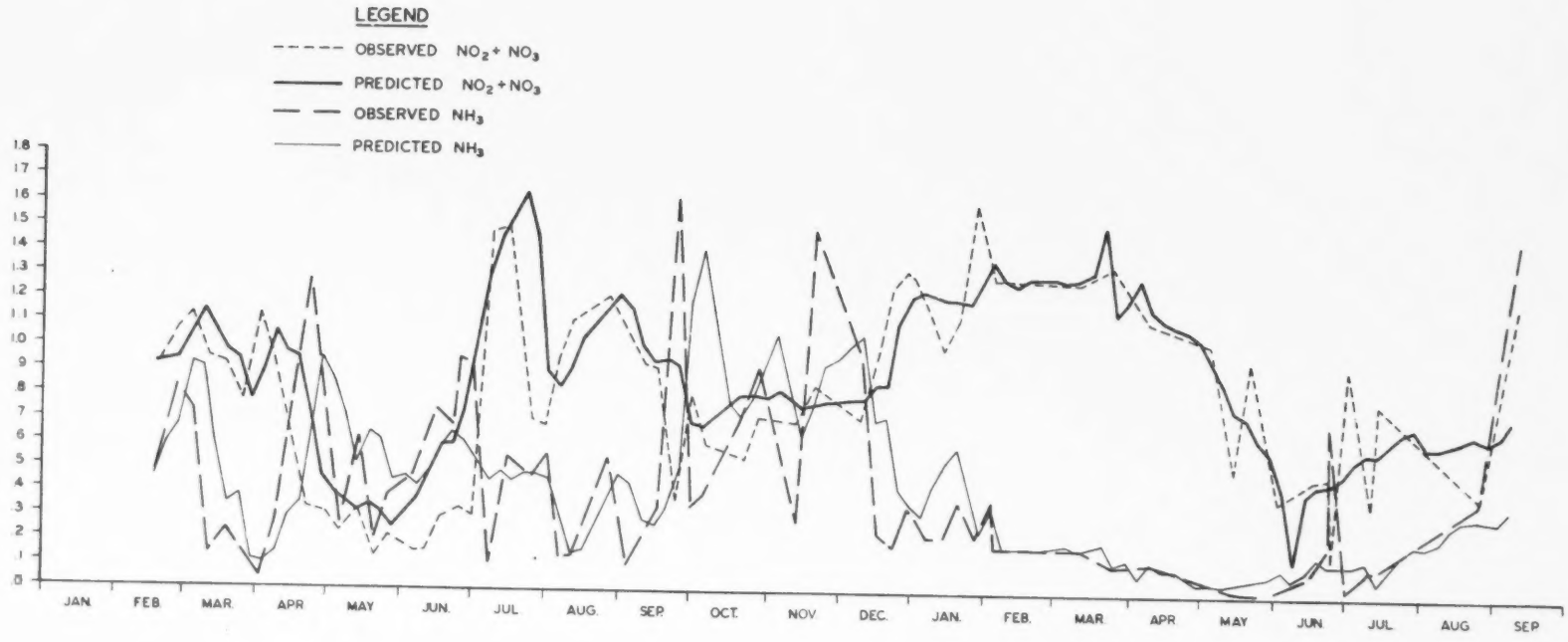


FIGURE VI-19

ANNUAL NITROGEN PROFILES
POTOMAC ESTUARY AT PISCATAWAY CREEK
1969 – 1970

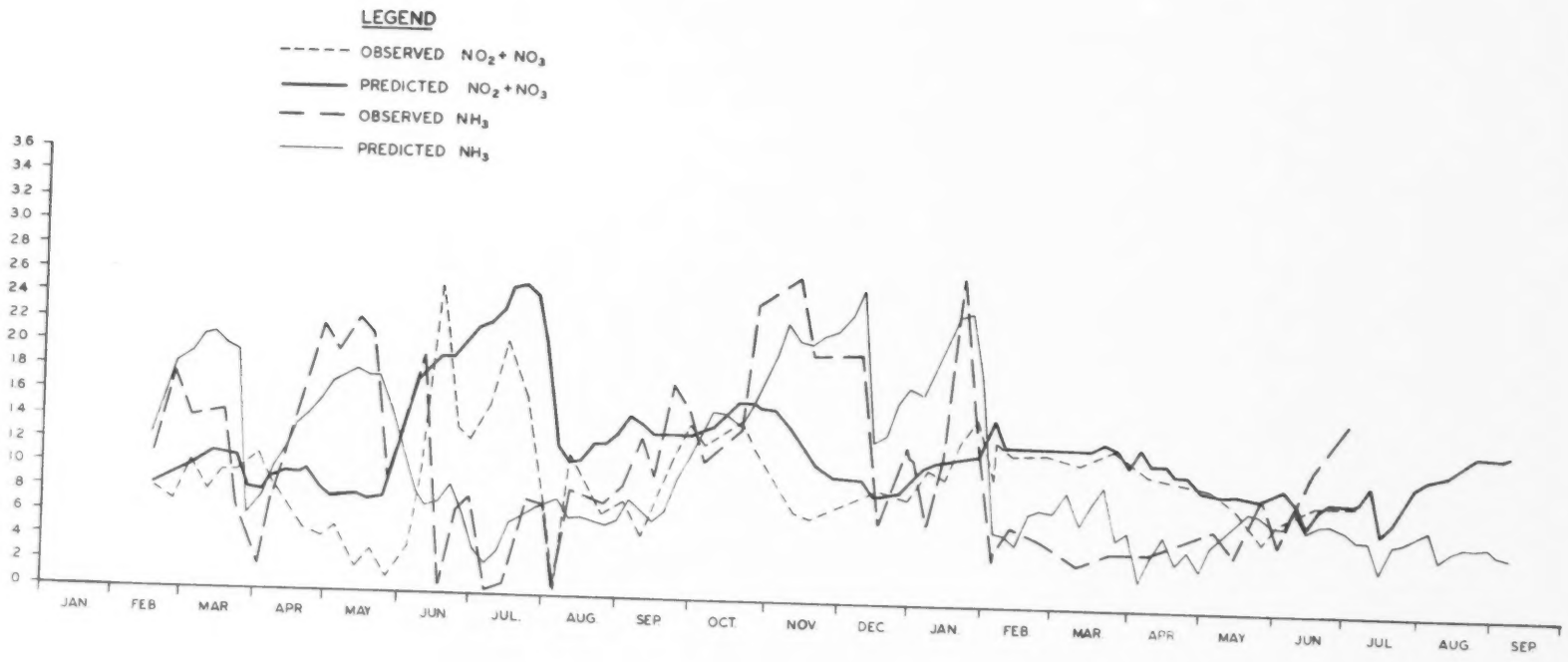


FIGURE VI-20

ANNUAL NITROGEN PROFILES
POTOMAC ESTUARY AT INDIAN HEAD
1969 – 1970

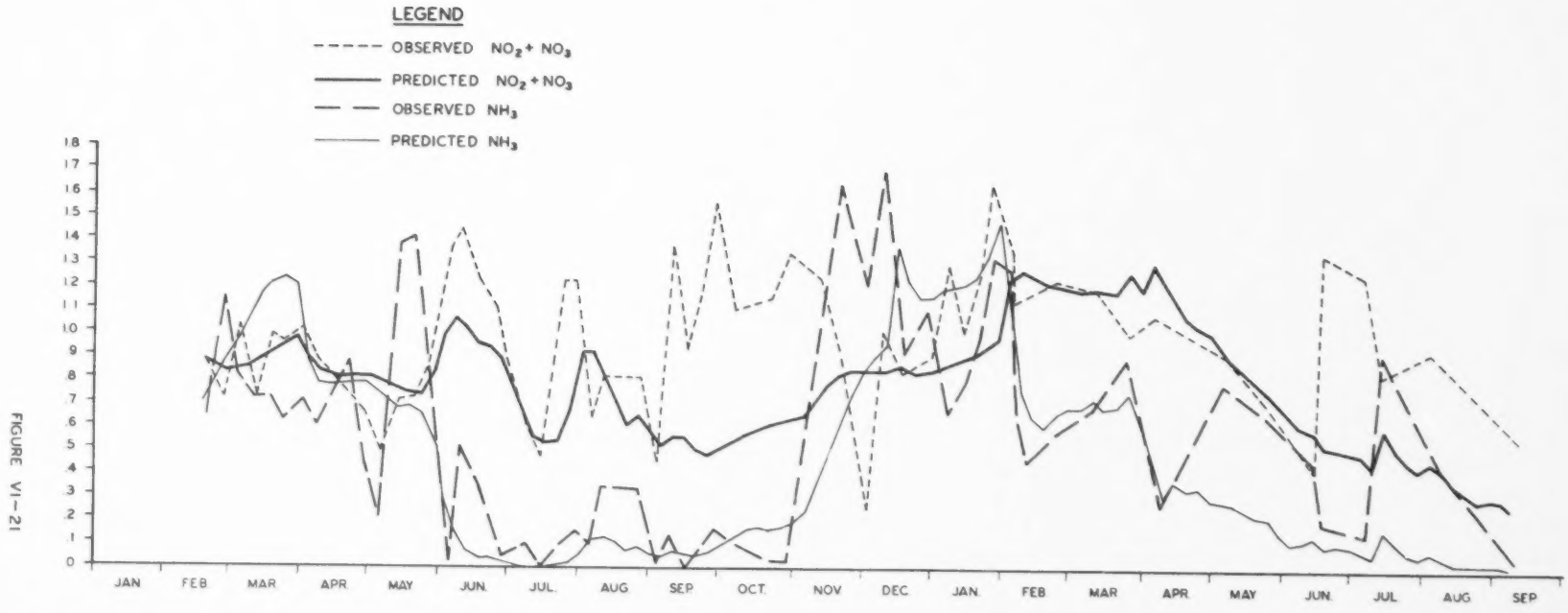


FIGURE VI-21

ANNUAL NITROGEN PROFILES
POTOMAC ESTUARY AT MARYLAND POINT
1969 – 1970

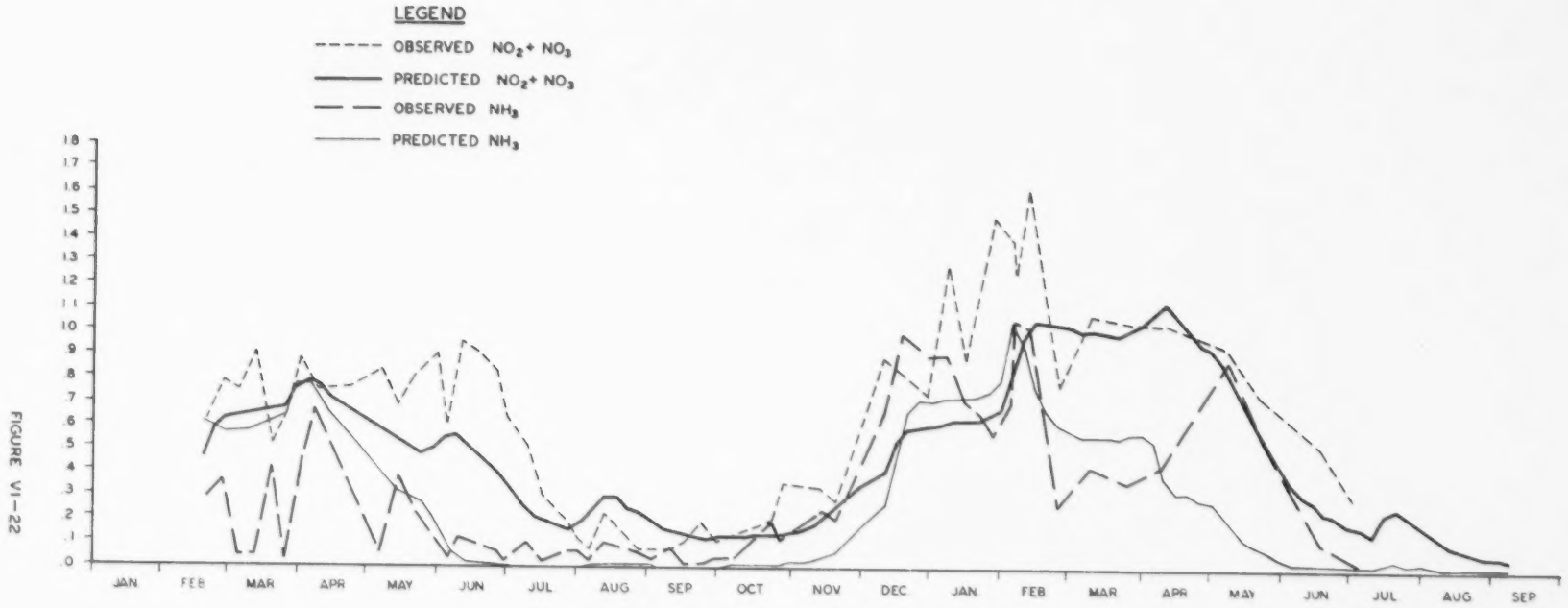


FIGURE VI-22

ANNUAL NITROGEN PROFILES
POTOMAC ESTUARY AT PINEY POINT
1969 – 1970

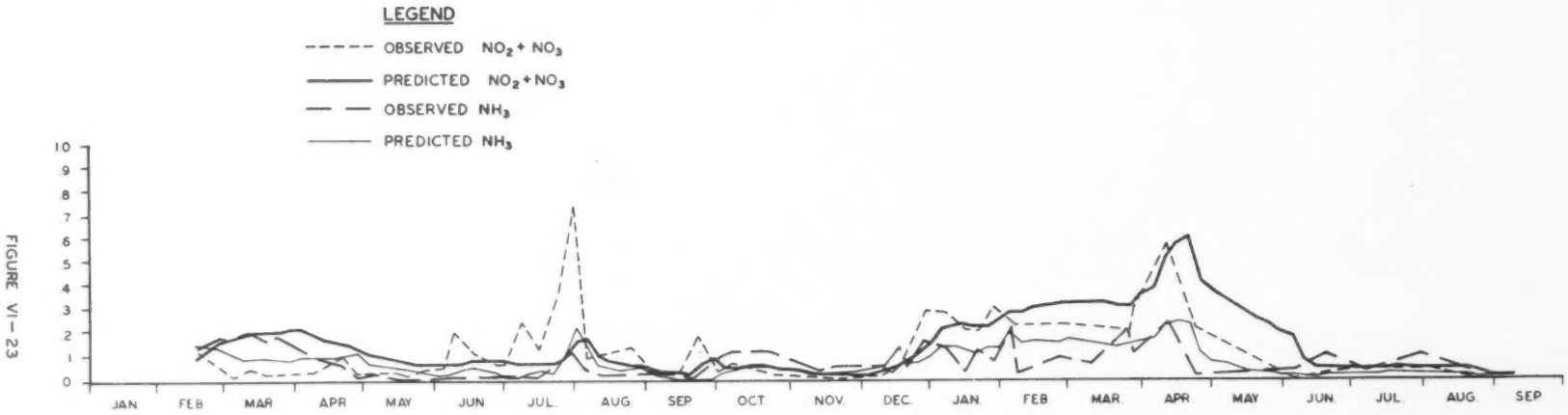


FIGURE VI – 23

D. CHLOROPHYLL PREDICTIONS BASED ON NITROGEN ASSIMILATION BY THE BIOMASS

Subsequent to application of the Dynamic Estuary Model for determining reaction rates involving nitrogen in the Potomac Estuary, the next logical step pursued was to mathematically "link" the nitrogen cycle with algal production. The purpose of extending the DEM in this manner was essentially twofold: (1) to determine whether nitrogen was indeed the growth-rate-limiting nutrient in the middle estuary as indicated by other methods of analysis and (2) to establish permissible nitrogen concentrations and loadings for the maintenance of a balanced ecological system.

In order to simulate the standing crop of algae as measured by chlorophyll a, the DEM was modified to convert losses of nitrate nitrogen to algal biomass. As indicated previously, it appeared that biological assimilation of ammonia nitrogen was minimal since nitrification occurring upstream from bloom areas reduced its availability during high temperature periods. The mass conversion factor was estimated, from 1970 algal composition analysis data, to be 90.0. This inferred that a 1.0 mg loss of nitrate would create a chlorophyll a mass of 90 µg. Practically complete utilization of nitrogen by the algal cells was assumed.

Figures VI-24 through VI-31 present observed and predicted chlorophyll a profiles for the upper 40 miles of the Potomac Estuary based on the "surrogate" version of the DEM. Also shown are the flows, temperatures, and decay rates for which these data apply. From these mathematical model runs, it appears that the standing crop of algae,

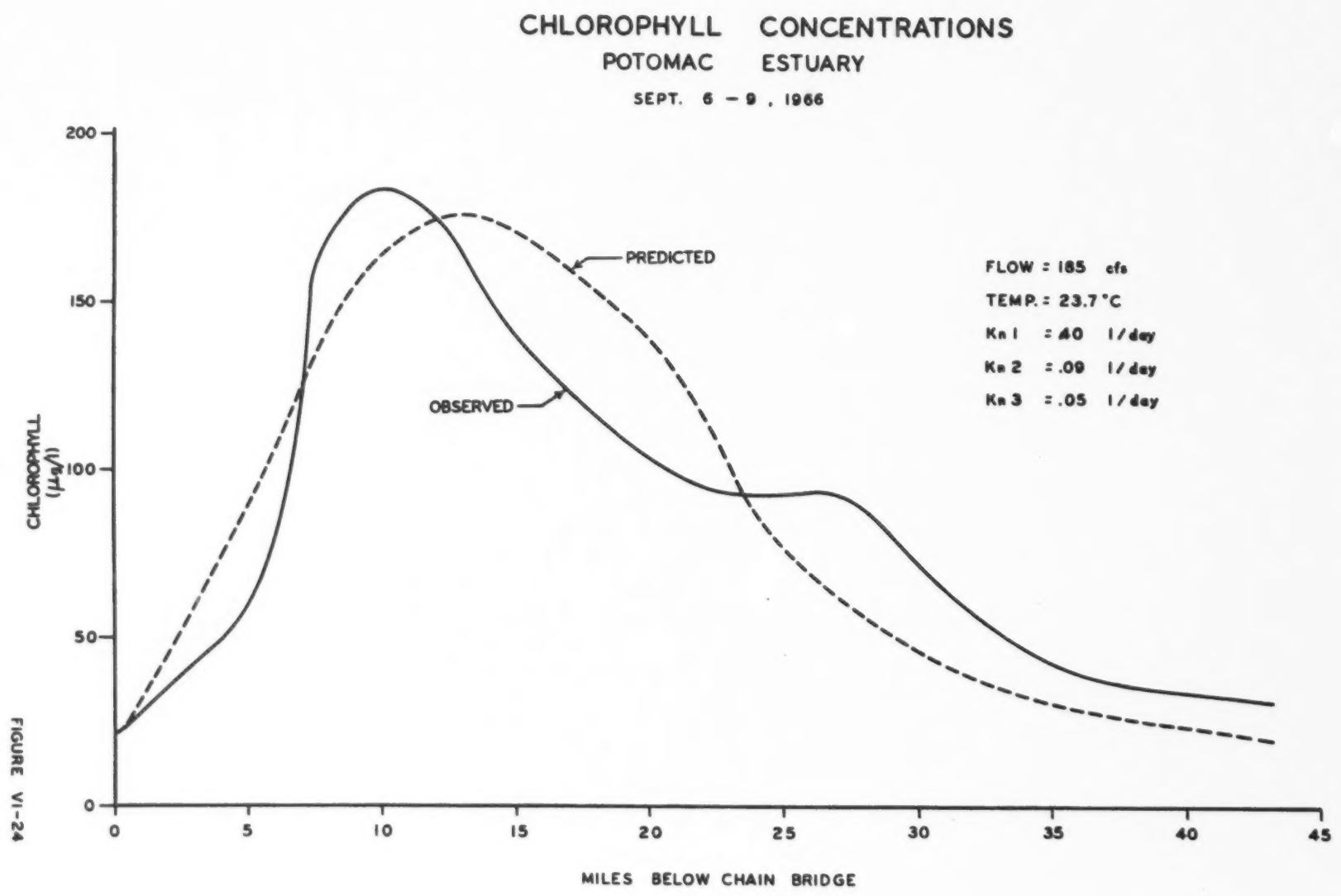

CHLOROPHYLL CONCENTRATIONS
POTOMAC ESTUARY
SEPT. 6 – 9, 1966
PREDICTED
OBSERVED
FLOW = 185 cfs
TEMP. = 23.7 °C
Kn 1 = .40 1/day
Kn 2 = .09 1/day
Kn 3 = .05 1/day
CHLOROPHYLL (µg/l)
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-24

CHLOROPHYLL CONCENTRATIONS

POTOMAC ESTUARY

OCT 7, 1968

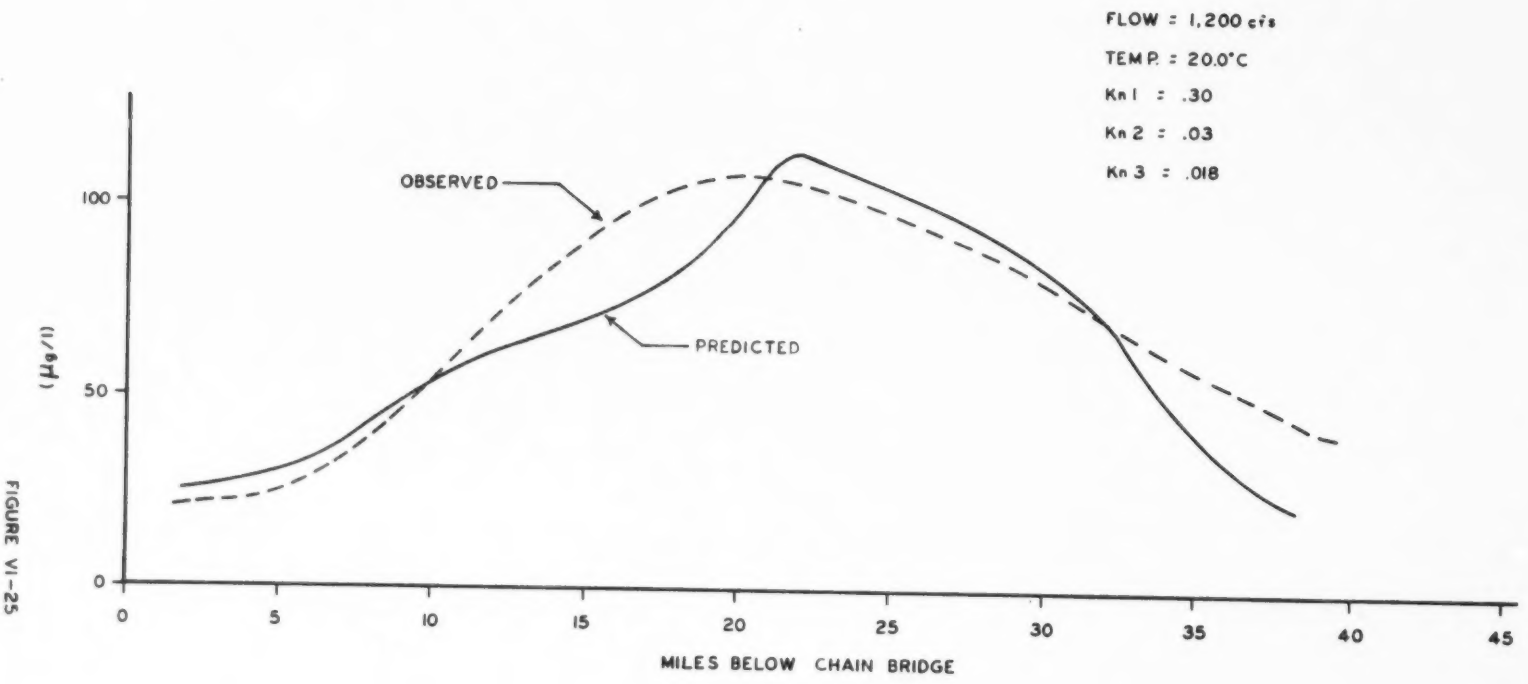


FIGURE VI-25

CHLOROPHYLL CONCENTRATIONS

POTOMAC ESTUARY

SEPT. 28 – 30, 1970

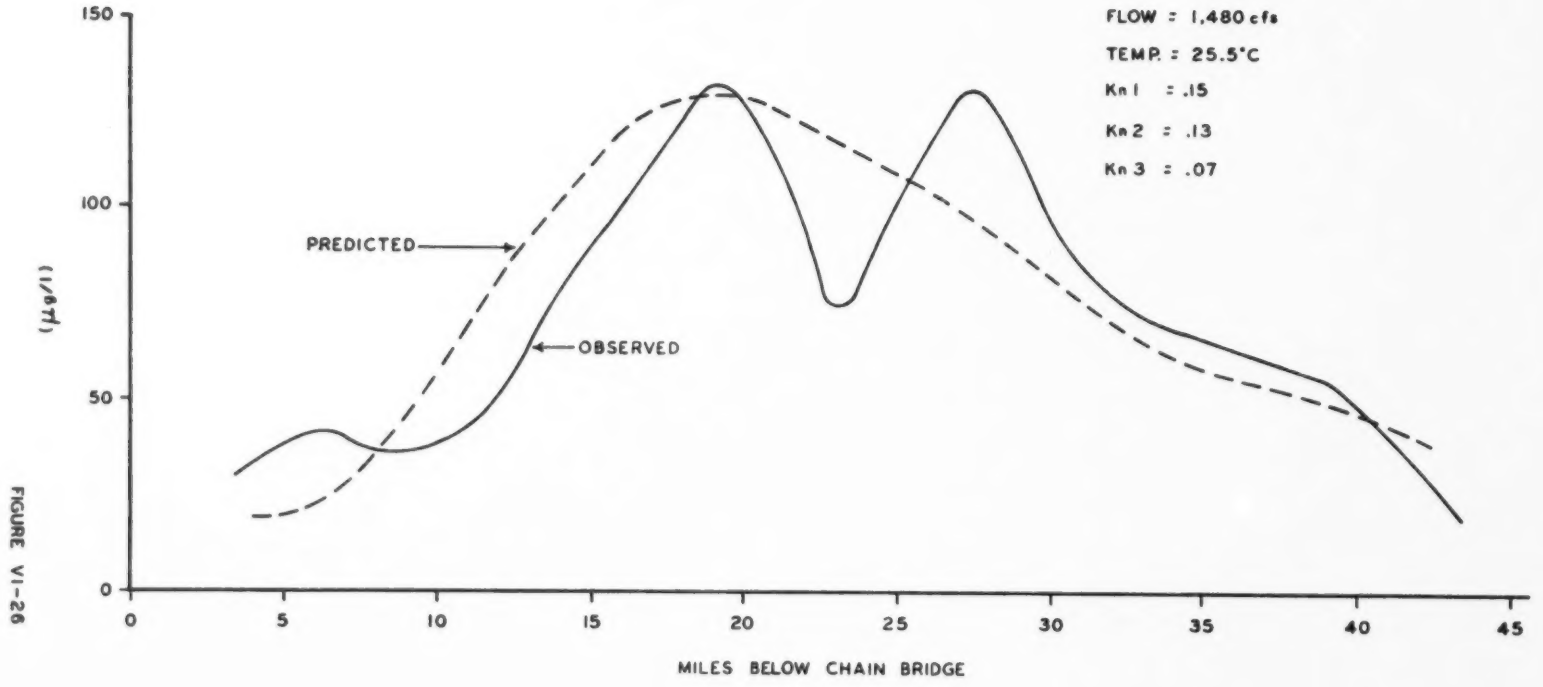


FIGURE VI-26

CHLOROPHYLL CONCENTRATIONS
POTOMAC ESTUARY
SEPT. 20 – 21, 1967

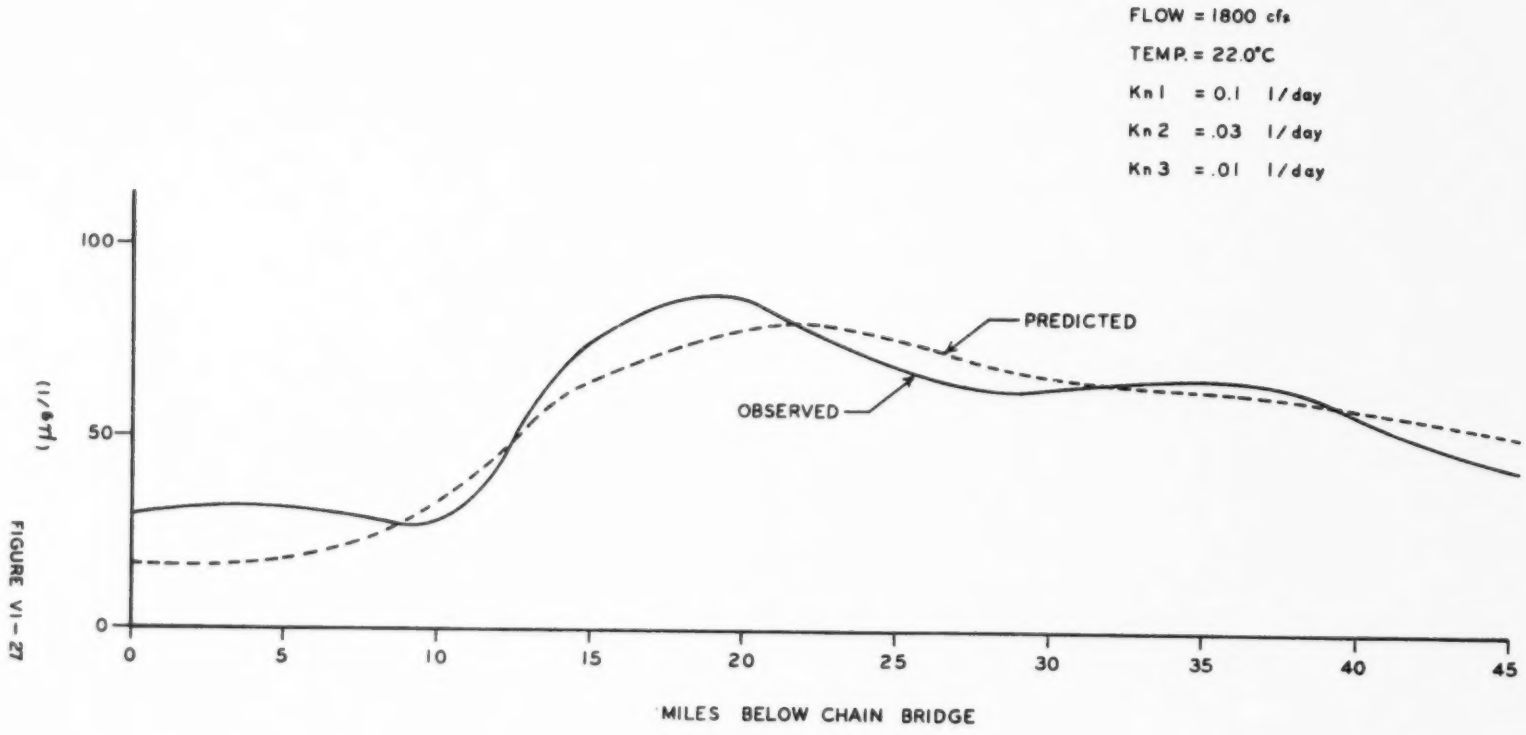


FIGURE VI-27

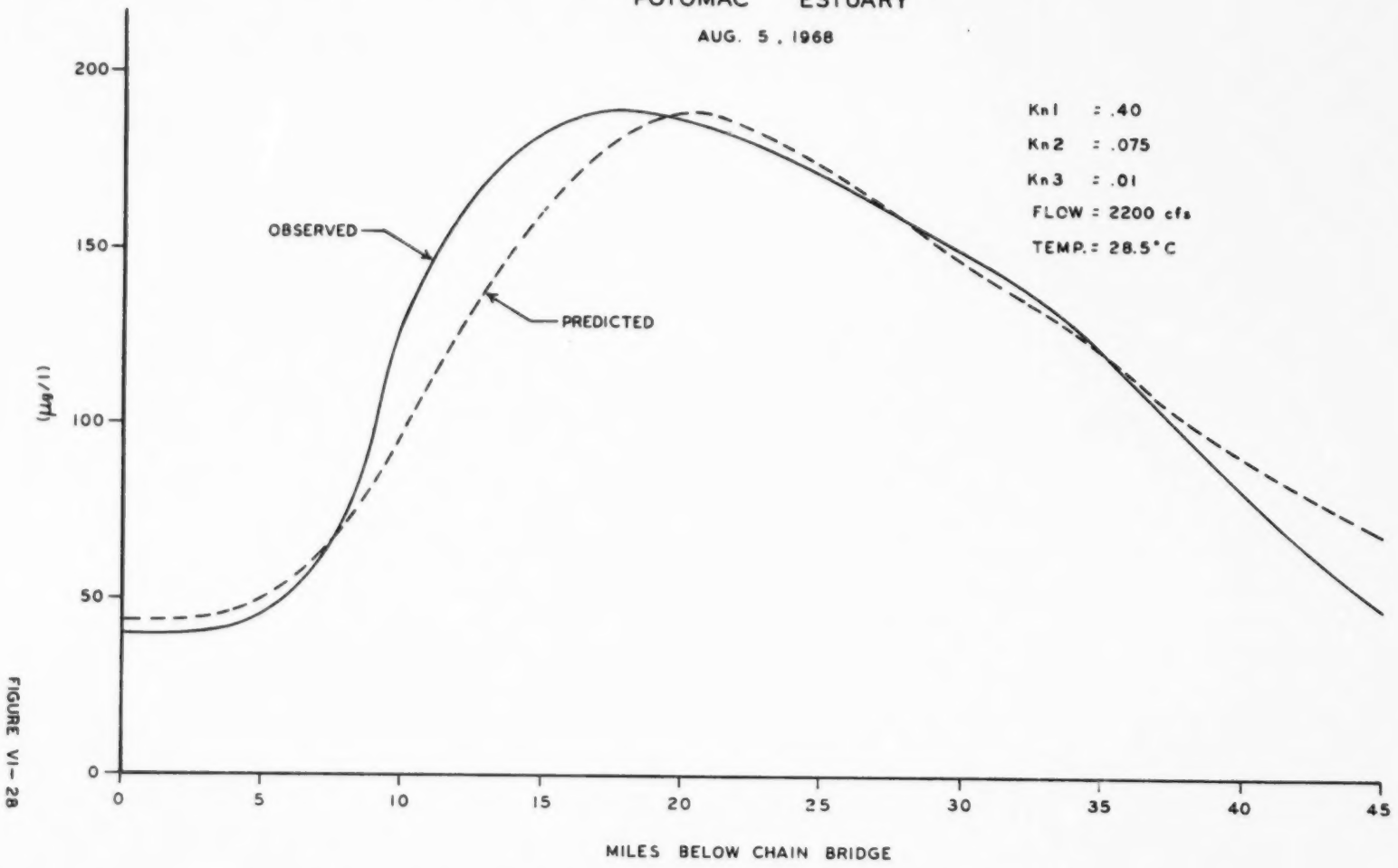

CHLOROPHYLL CONCENTRATIONS
POTOMAC ESTUARY
AUG. 5, 1968
Kn1 : .40
Kn2 : .075
Kn3 : .01
FLOW = 2200 cfs
TEMP. = 28.5°C
OBSERVED
PREDICTED
(µg/l)
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-28

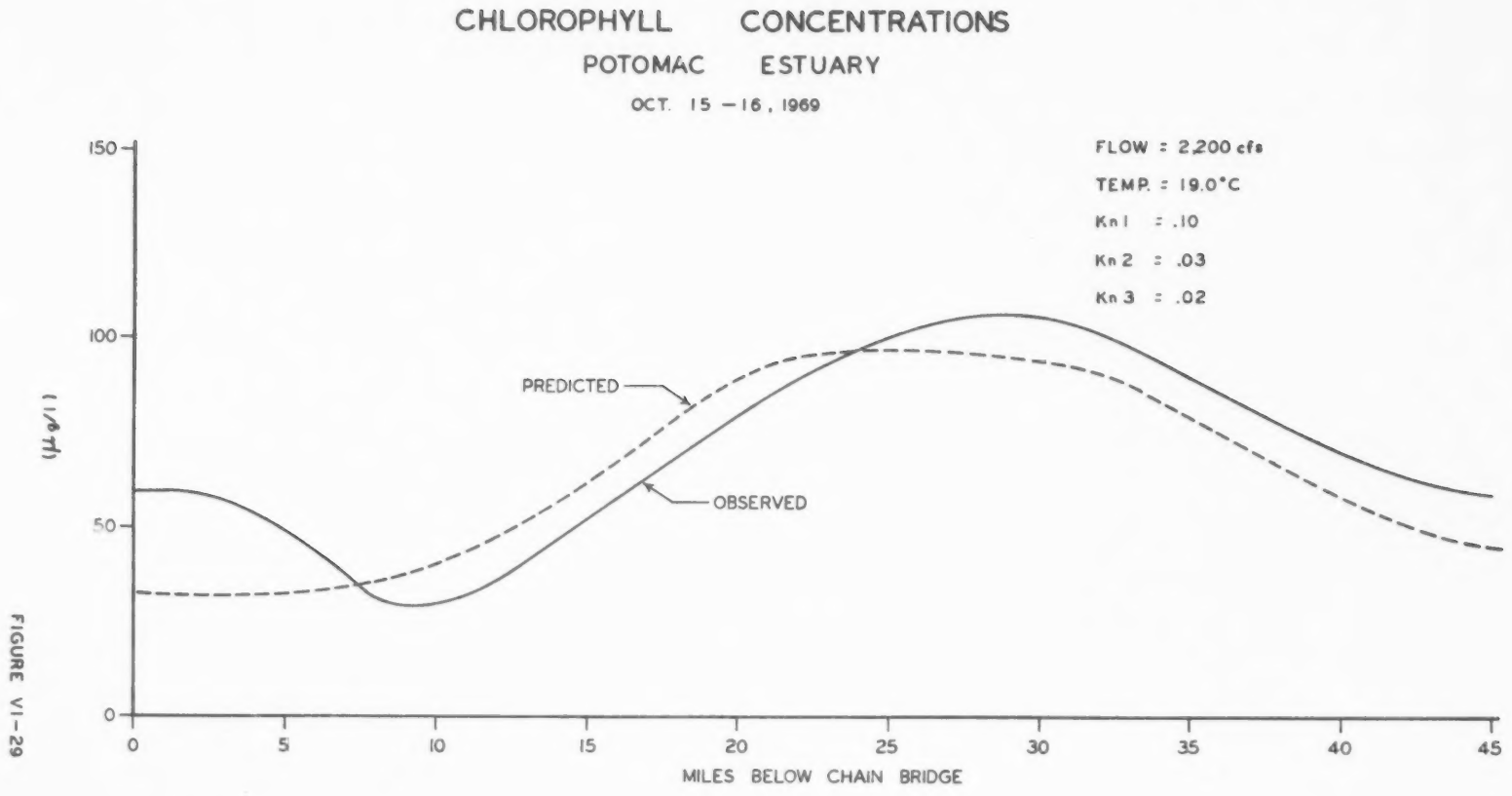

CHLOROPHYLL CONCENTRATIONS
POTOMAC ESTUARY
OCT. 15 – 16, 1969
FLOW = 2,200 cfs
TEMP. = 19.0°C
Kn 1 = .10
Kn 2 = .03
Kn 3 = .02
PREDICTED
OBSERVED
(µg/l)
150
100
50
0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-29

CHLOROPHYLL CONCENTRATIONS

POTOMAC ESTUARY

AUGUST 19-23, 1968

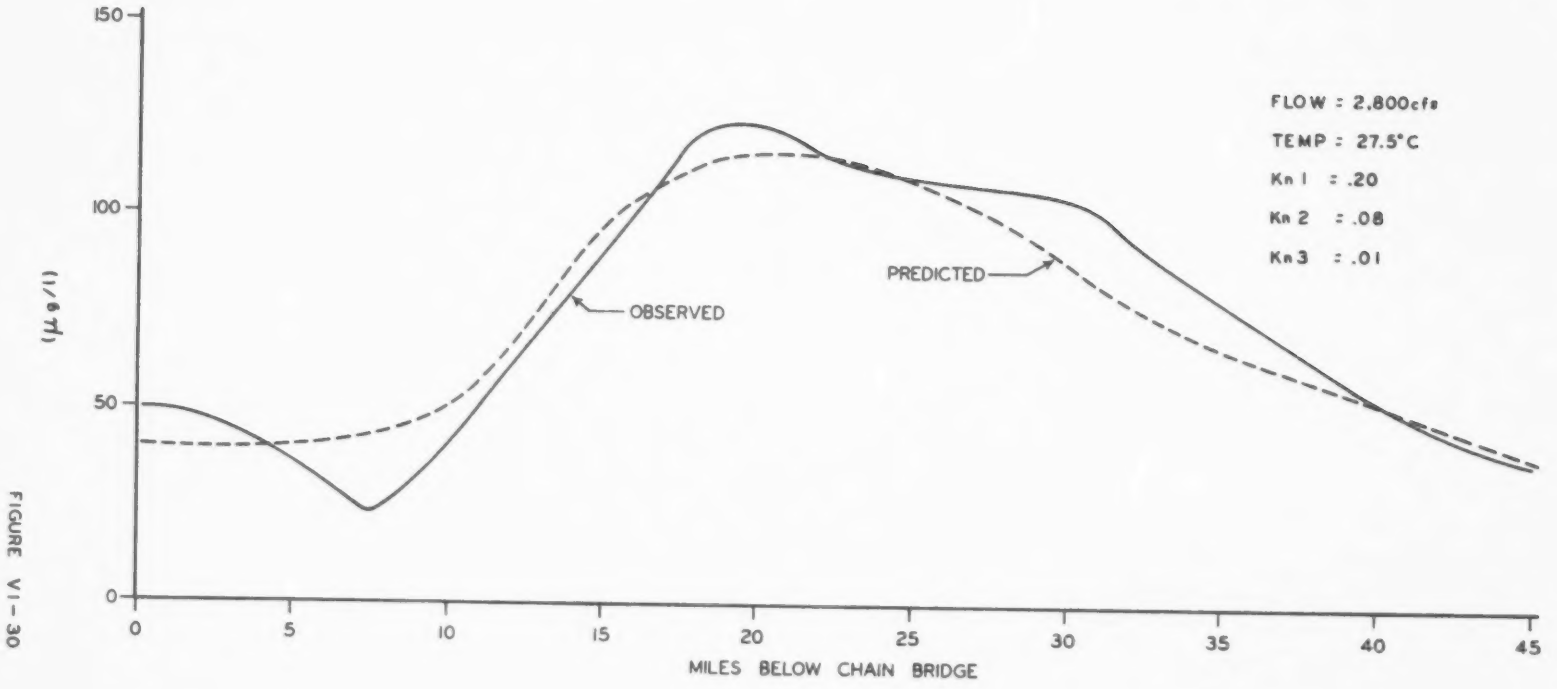


FIGURE V1-30

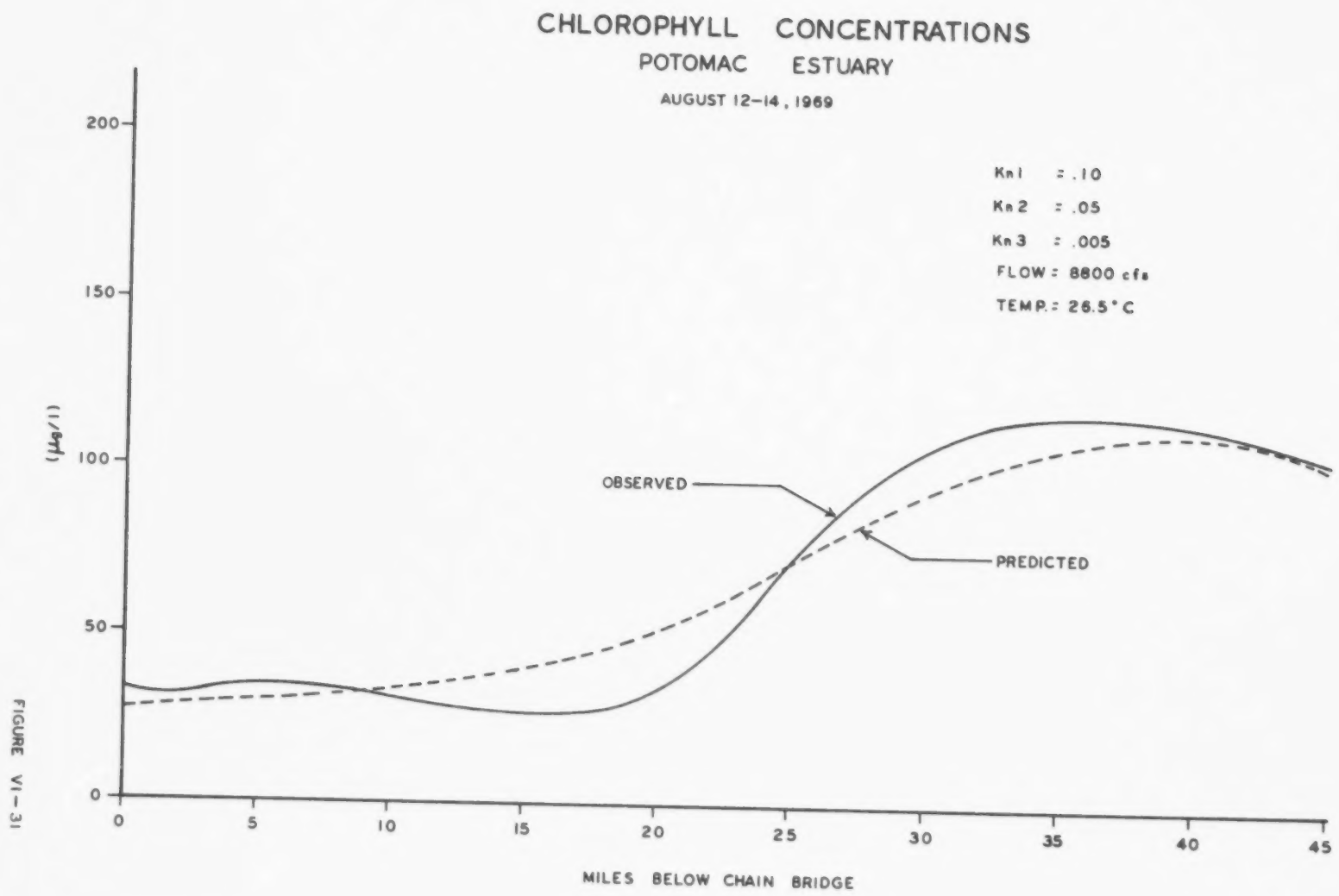

CHLOROPHYLL CONCENTRATIONS
POTOMAC ESTUARY
AUGUST 12–14, 1969
Kn1 = .10
Kn2 = .05
Kn3 = .005
FLOW = 8800 cfs
TEMP. = 26.5°C
(µg/l)
200
150
100
50
0
OBSERVED
PREDICTED
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VI-31

CHAPTER VII

PHOSPHORUS ASSIMILATION AND TRANSPORT

A. TEMPORAL AND SPATIAL DISTRIBUTION

Like nitrogen, the distribution of phosphorus in the Potomac Estuary is strongly dependent upon such factors as temperature, biological activity, and freshwater flow rates. Figure VII-1 shows, by means of an isopleth, the spatial distribution of inorganic phosphorus during 1969 and 1970. Of special importance are the maximum concentrations of 2.0 to 2.5 mg/l (as PO_4) which were observed between Bellevue (River Mile 10) and Piscataway Creek (River Mile 18) during the low-flow periods of June, July, October, and early November 1969. The month of August (1969) was characterized by abnormally high flows and low phosphorus levels, the result of phosphorus deposition by adsorption onto silt particles during high flow periods.

A similar occurrence had been observed previously (March 1967) and it was concluded that, while periods of high freshwater inflows contribute an excessive phosphorus load, the overall effects of adsorption and deposition produce a net decrease in phosphorus during these periods in the upper Potomac Estuary.

Inorganic phosphorus concentrations upstream from Hains Point (River Mile 7.6) were usually less than 0.5 mg/l. Downstream from Piscataway Creek, inorganic phosphorus levels decreased appreciably during high temperature periods due to continued deposition and bio-

INORGANIC PHOSPHORUS ISOPLETH

POTOMAC ESTUARY

1969-1970 DATA

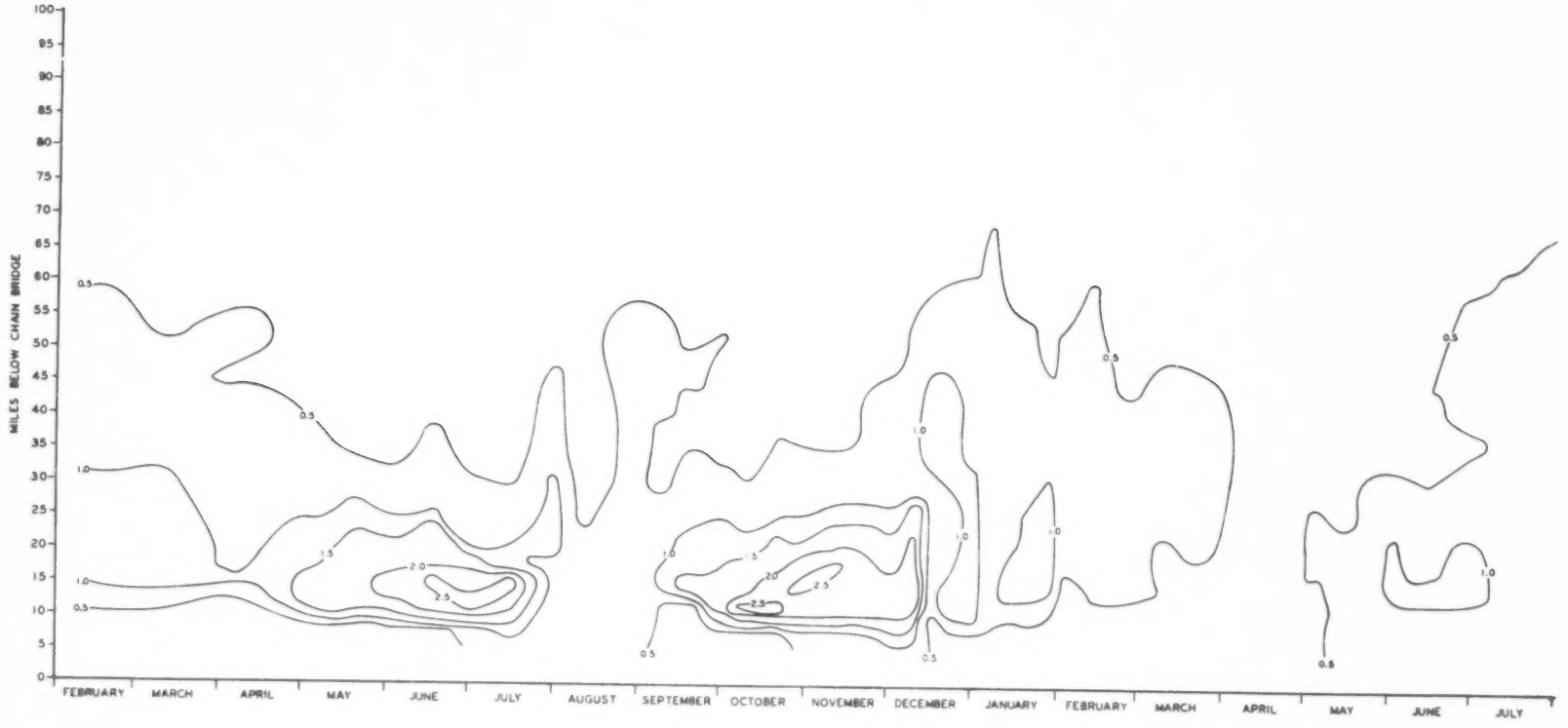


FIGURE VII-1

TOTAL PHOSPHORUS ISOPLETH

POTOMAC ESTUARY

1969-1970 DATA

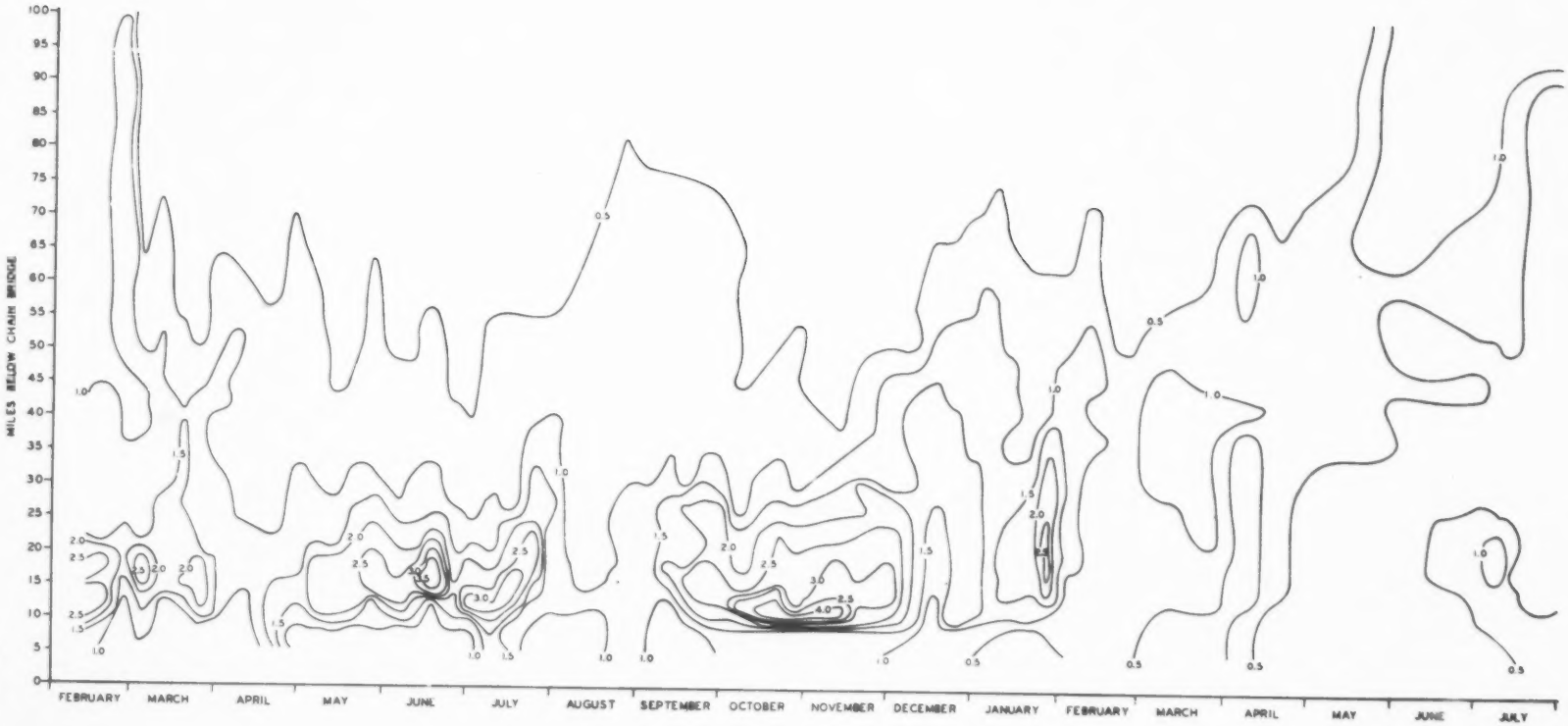


FIGURE VII-2

B. DETERMINATION OF LOSS RATE AND TEMPERATURE EFFECTS

Water quality sampling data collected in the upper Potomac Estuary from fourteen separate surveys were used for purposes of Dynamic Estuary Model verification, and more specifically, to determine the magnitude of the overall phosphorus loss rate. During these model studies, no distinction was made as to the relative importance of (1) deposition to bottom muds and (2) biological uptake by algal cells. All of the sampling data were collected under relatively steady-state flow conditions, ranging from 185 cfs to 11,000 cfs. A range in water temperatures, from 1.0°C to 28.5°C, was also represented.

Figures VII-3 through VII-16 depict the observed total phosphorus and inorganic phosphorus profiles in the upper 45 miles of estuary, as well as the model predictions for total phosphorus. The close relationship between observed TP and Pi data eliminated the necessity for separate simulations. An examination of these figures will indicate that the magnitude of peak concentrations and the rate of decrease in phosphorus downstream from those peaks were accurately simulated. In order to obtain this agreement with the model, it was necessary to utilize second-order kinetics having the following form:

$$\frac{dc}{dt} = -kc^2.$$

where c = concentration

t = time

and k = reaction rate (gr/day)

The reaction rates required for model verification were greatly affected by temperature, as can be seen in Figure VII-17.

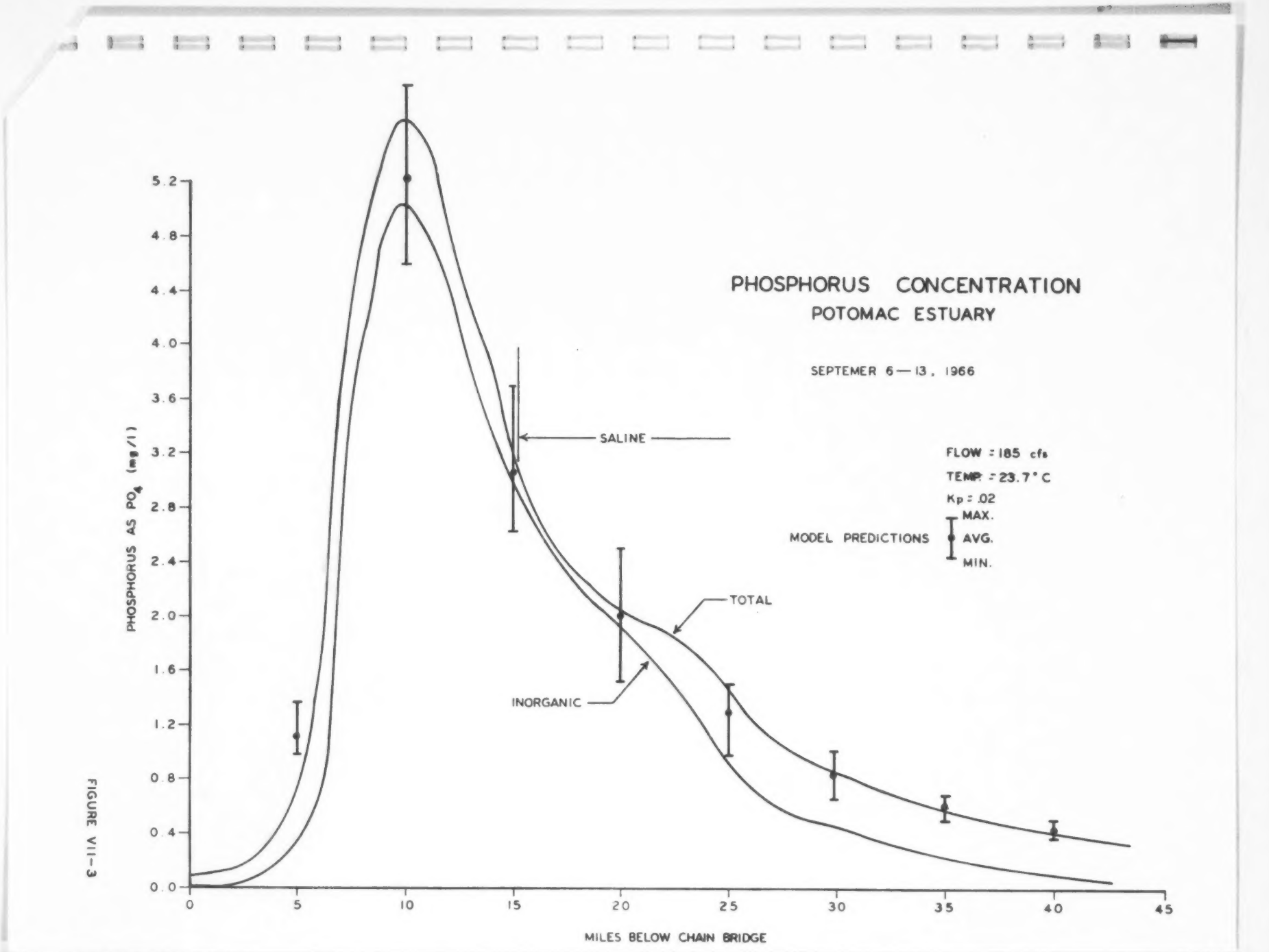


FIGURE VIII-3

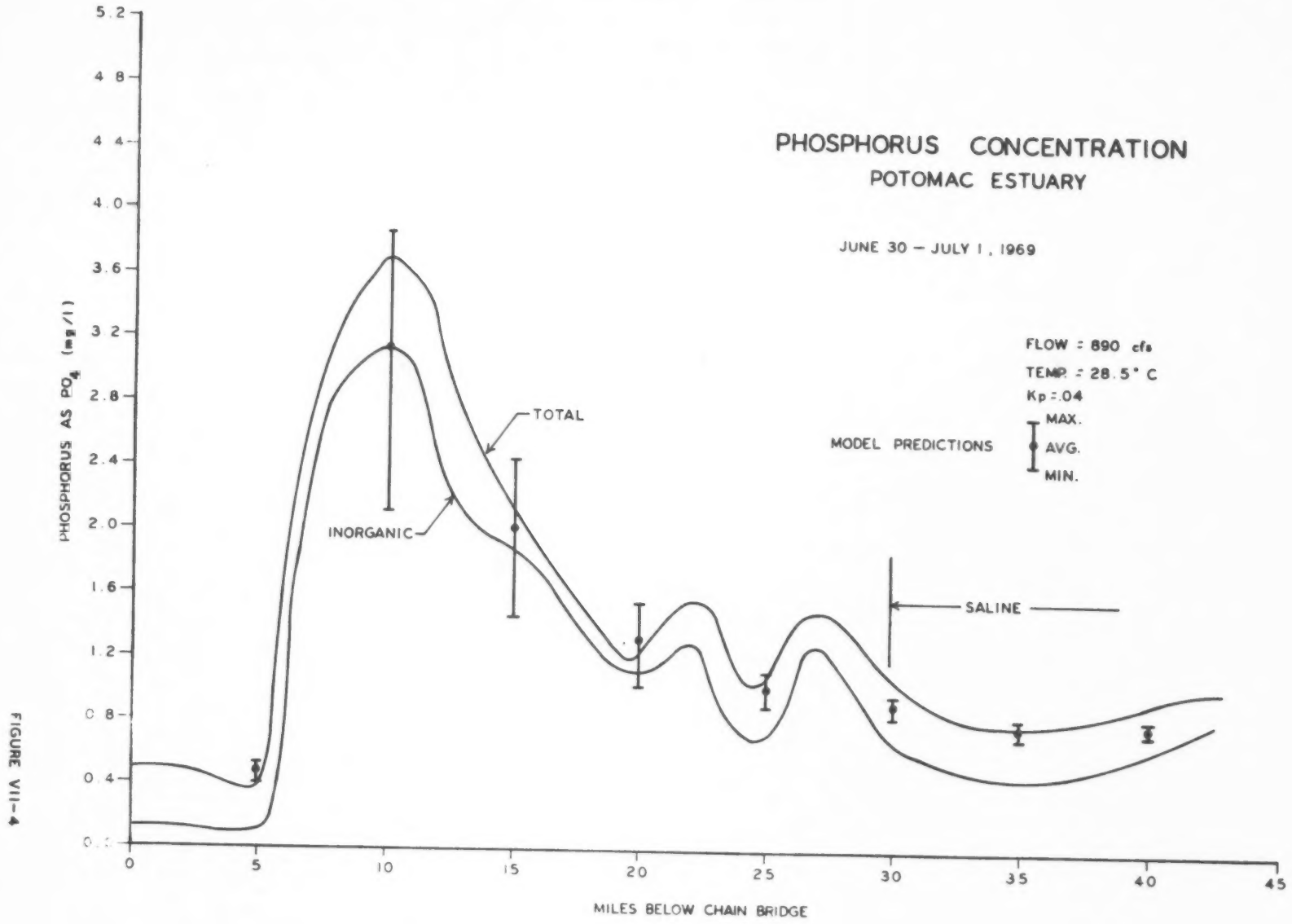

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
JUNE 30 – JULY 1, 1969
FLOW = 890 cfs
TEMP. = 28.5° C
Kp = .04
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL
INORGANIC
SALINE
PHOSPHORUS AS PO_4 (mg/l)
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE VII-4

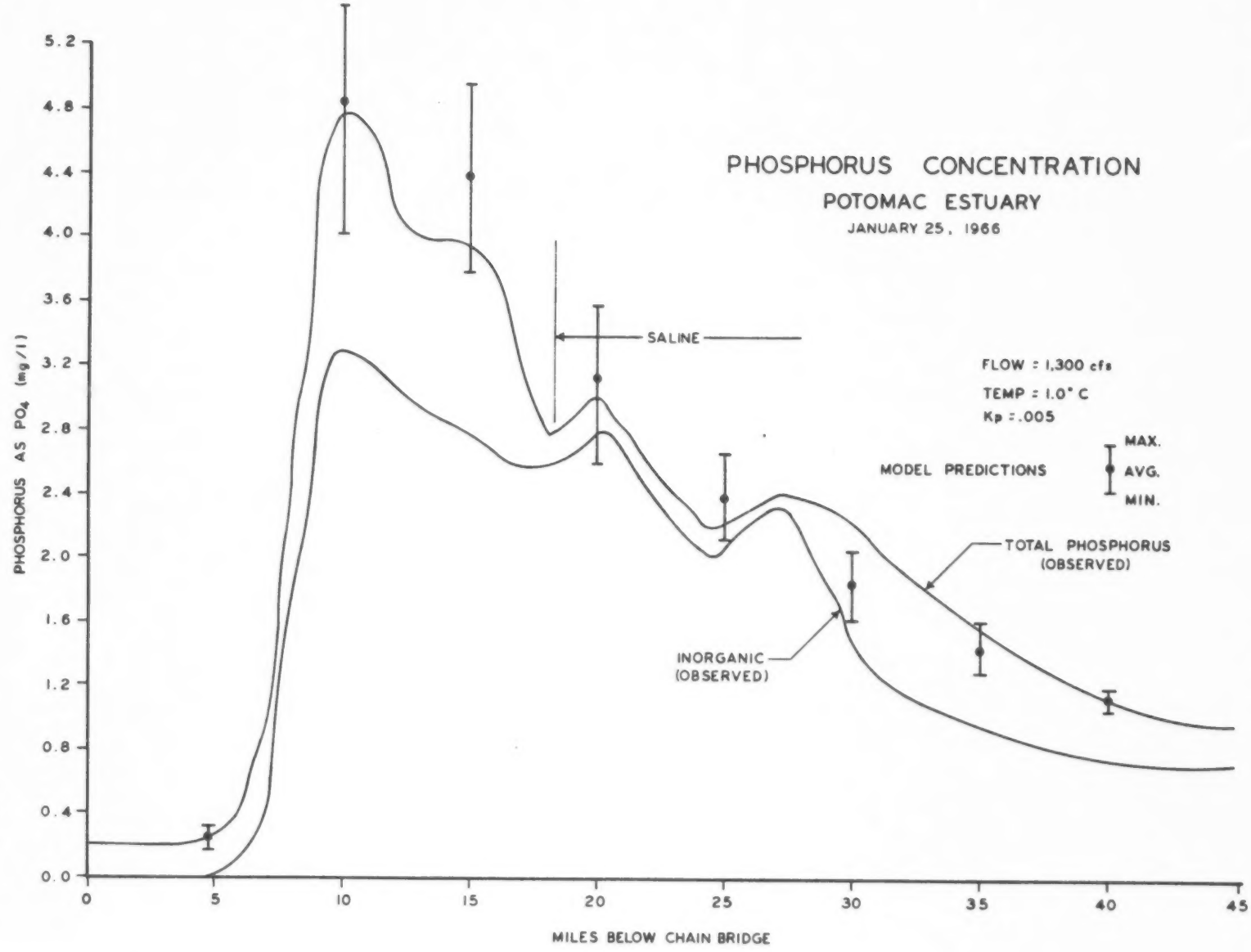

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
JANUARY 25, 1966
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
SALINE
FLOW = 1,300 cfs
TEMP = 1.0° C
Kp = .005
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL PHOSPHORUS (OBSERVED)
INORGANIC (OBSERVED)
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE VII-5

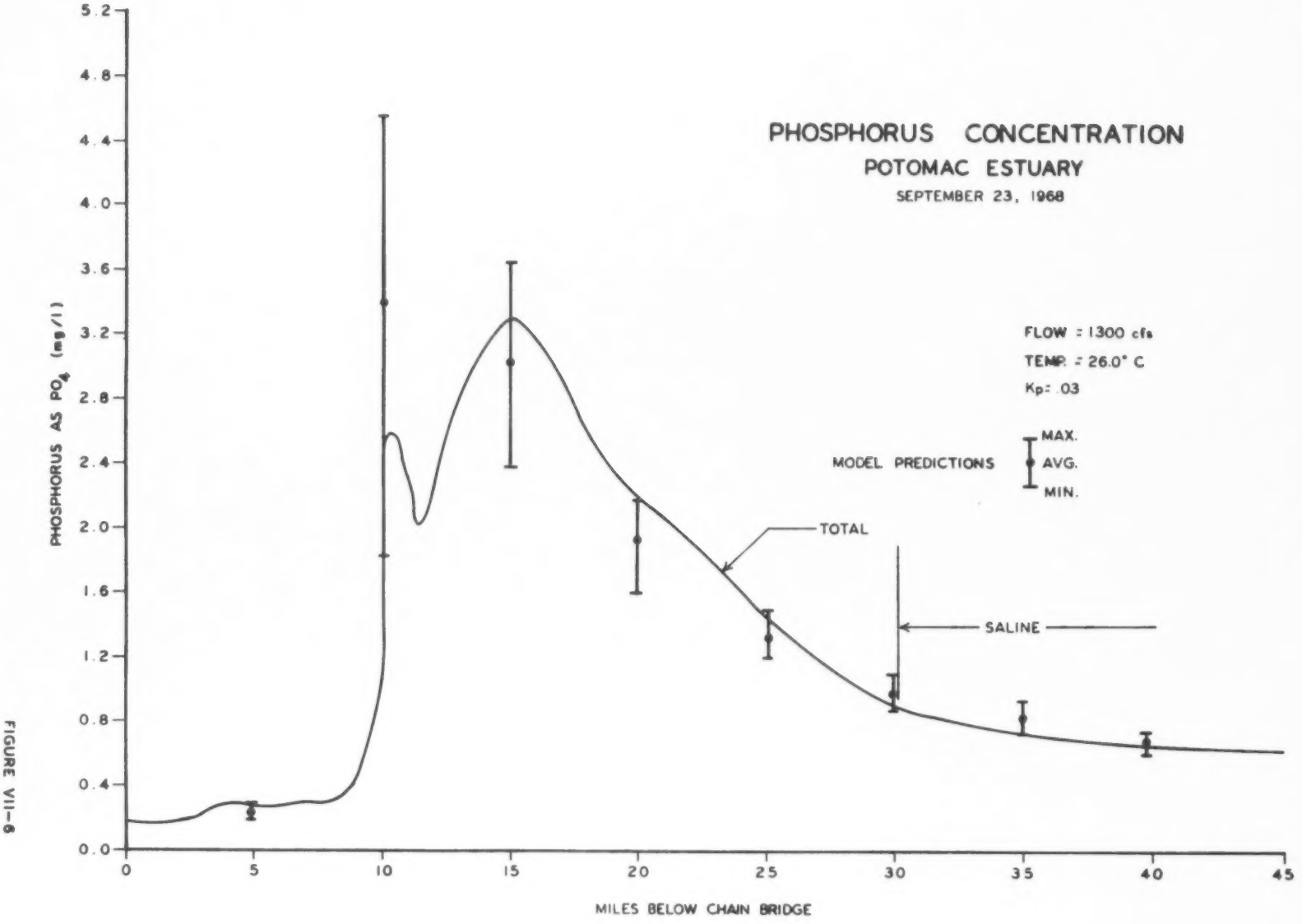

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
SEPTEMBER 23, 1968
FLOW = 1300 cfs
TEMP. = 26.0° C
Kp = .03
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL
SALINE
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE VII-9

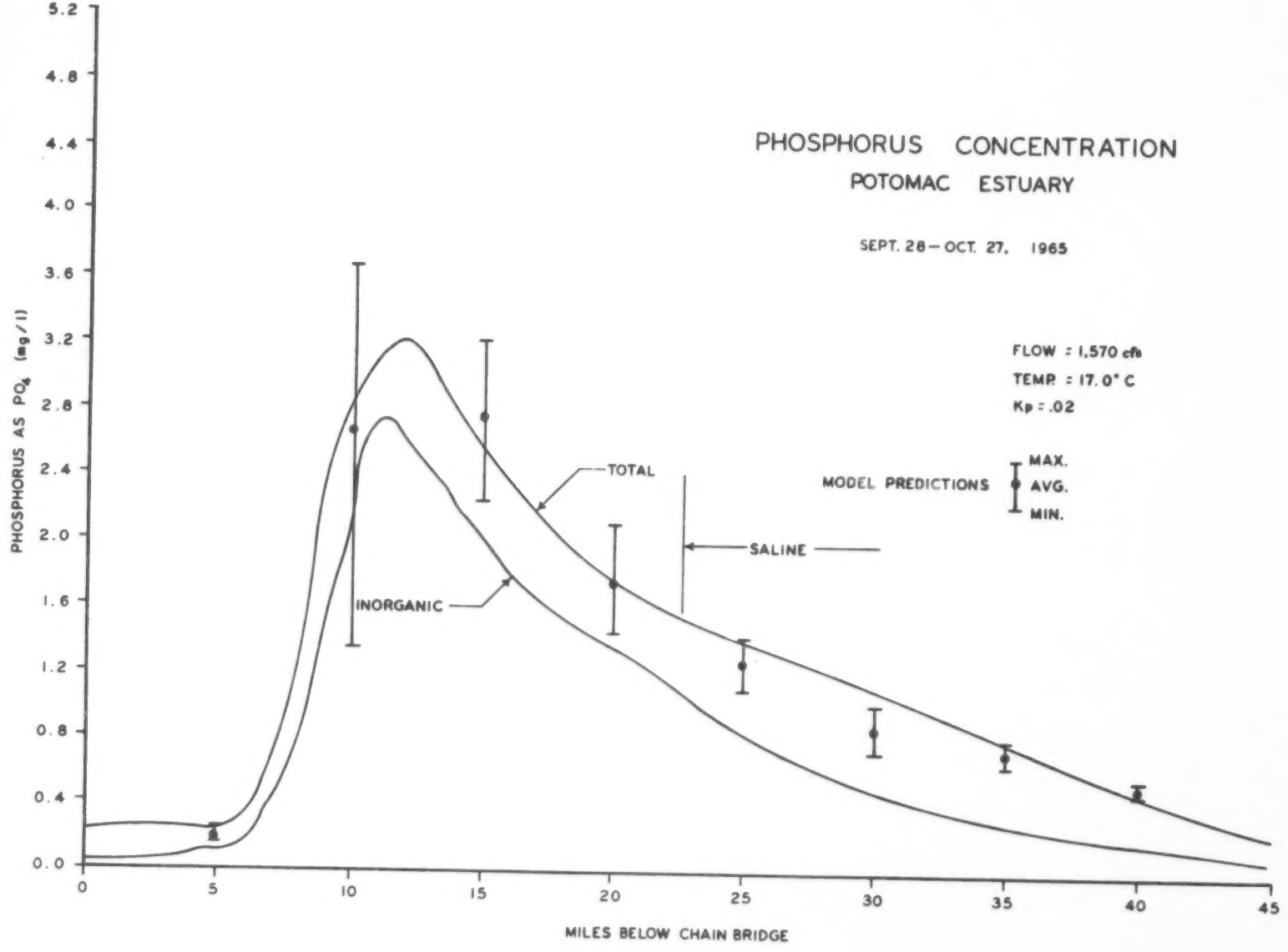

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
SEPT. 28 – OCT. 27, 1965
FLOW = 1,570 cfs
TEMP. = 17.0° C
Kp = .02
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL
SALINE
INORGANIC
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE VII-7

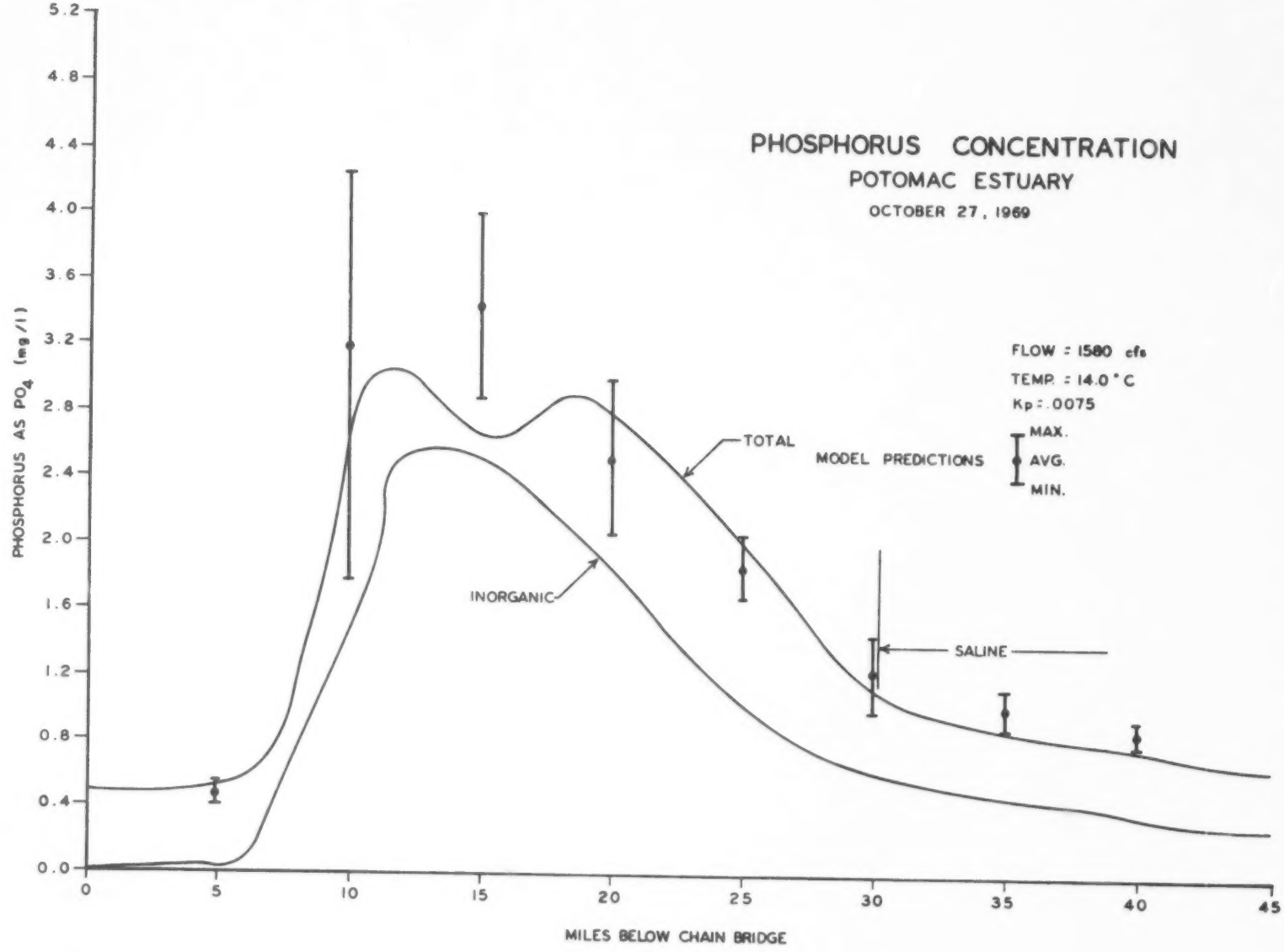

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
OCTOBER 27, 1969
FLOW = 1580 cfs
TEMP. = 14.0 °C
Kp = .0075
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL
INORGANIC
SALINE
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE VII-8

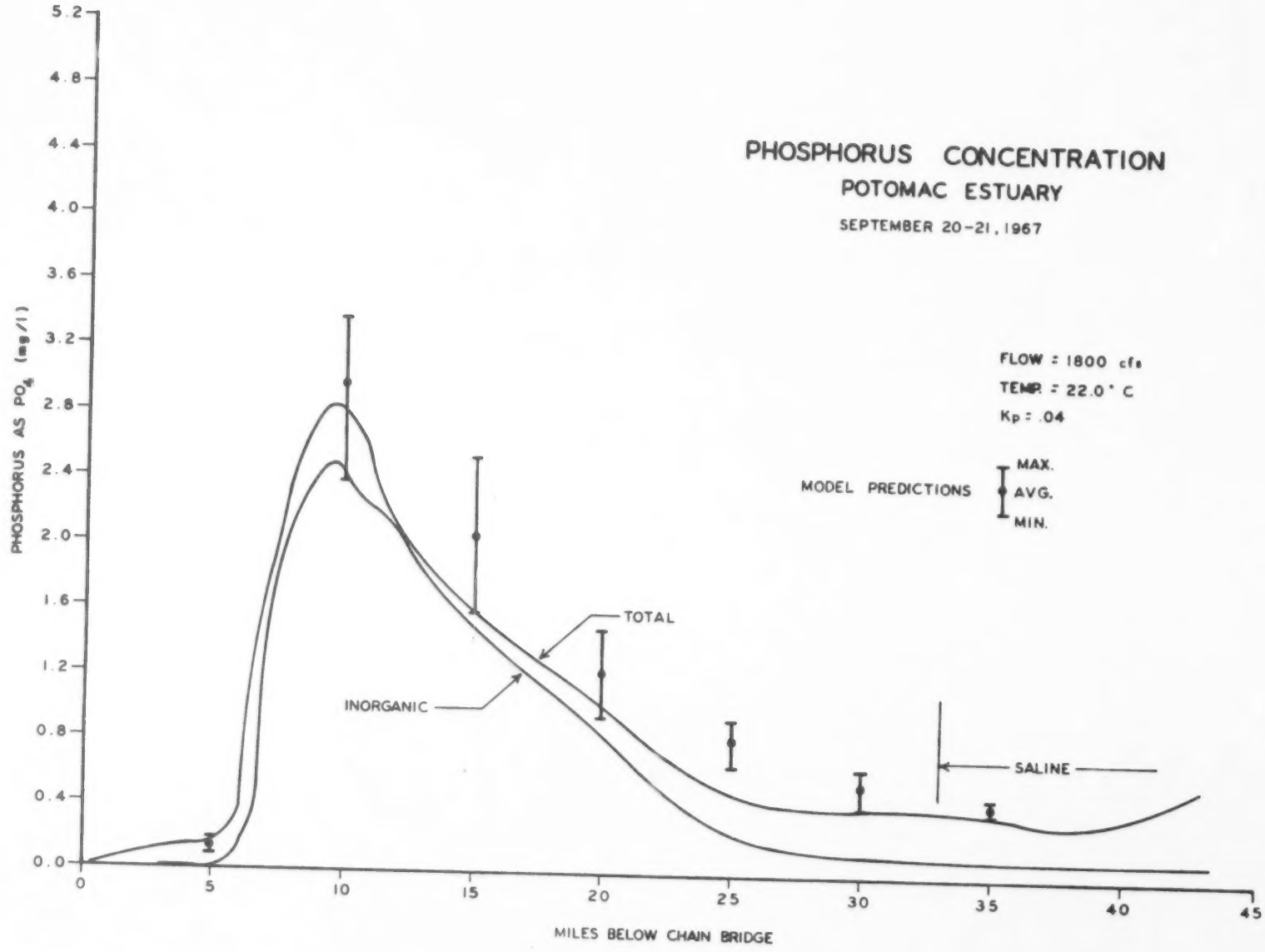

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
SEPTEMBER 20-21, 1967
FLOW = 1800 cfs
TEMP. = 22.0° C
Kp = .04
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL
INORGANIC
SALINE
PHOSPHORUS AS PO4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE VII-9

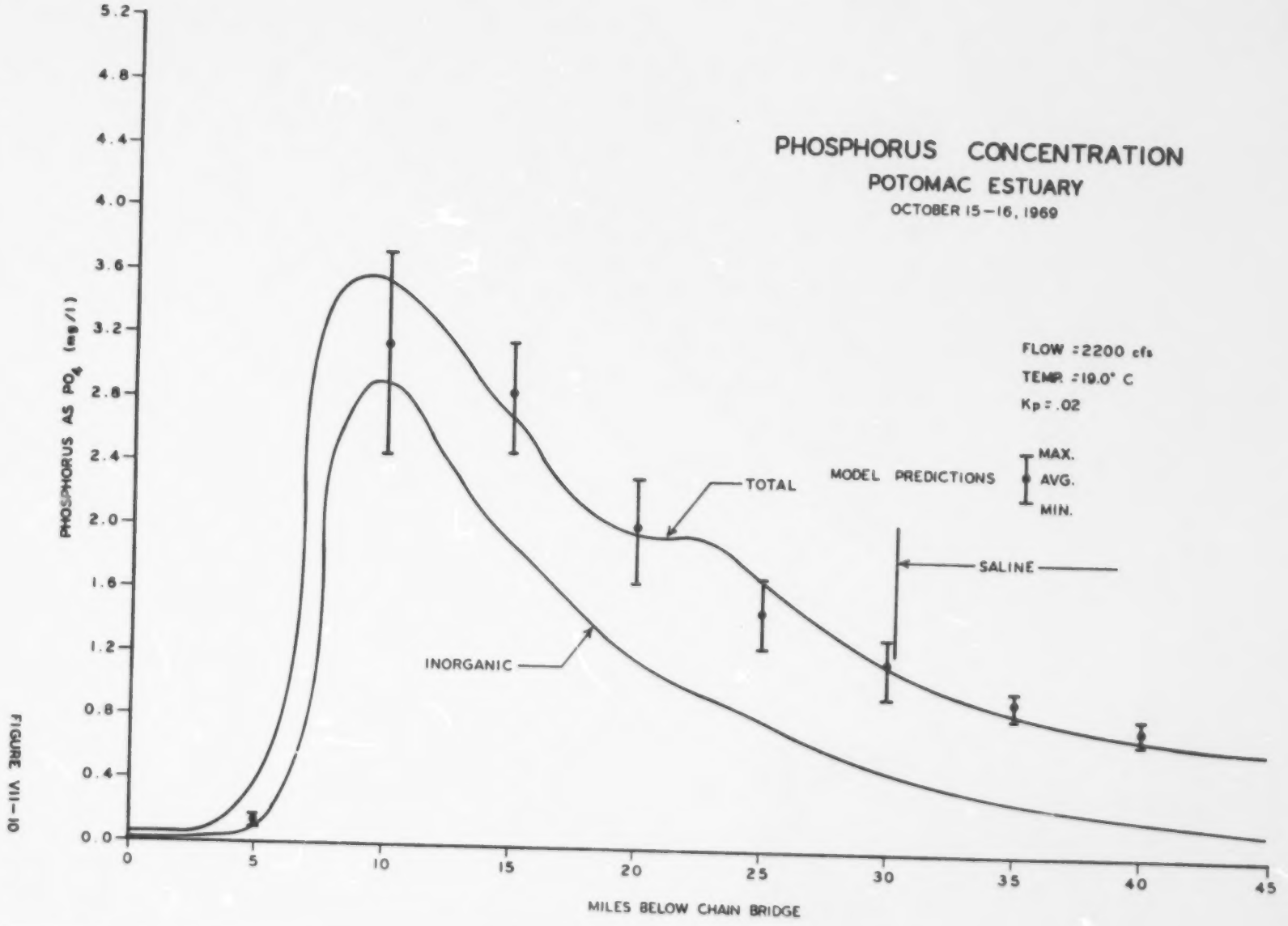


FIGURE VII-10

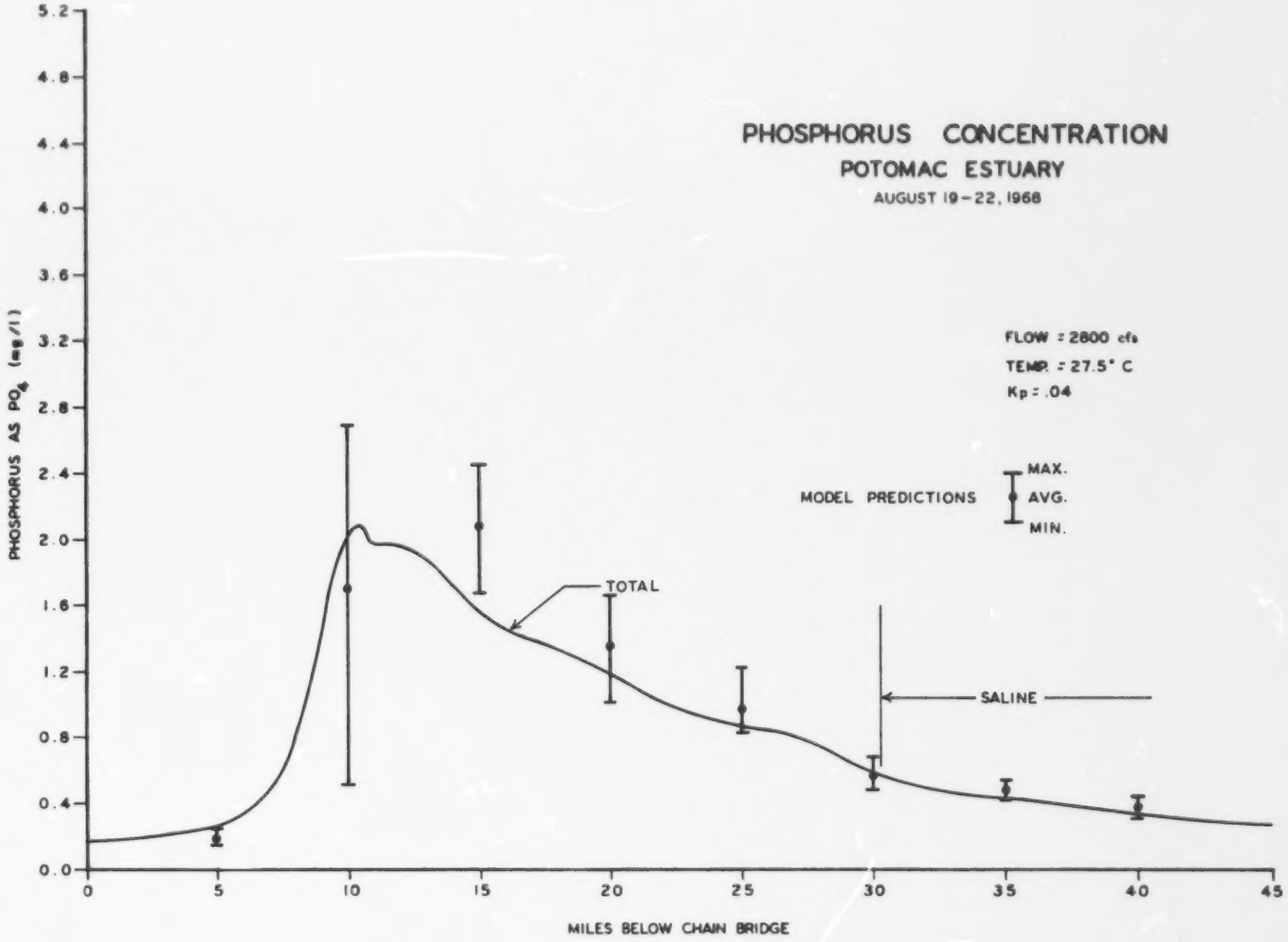


FIGURE VII-11

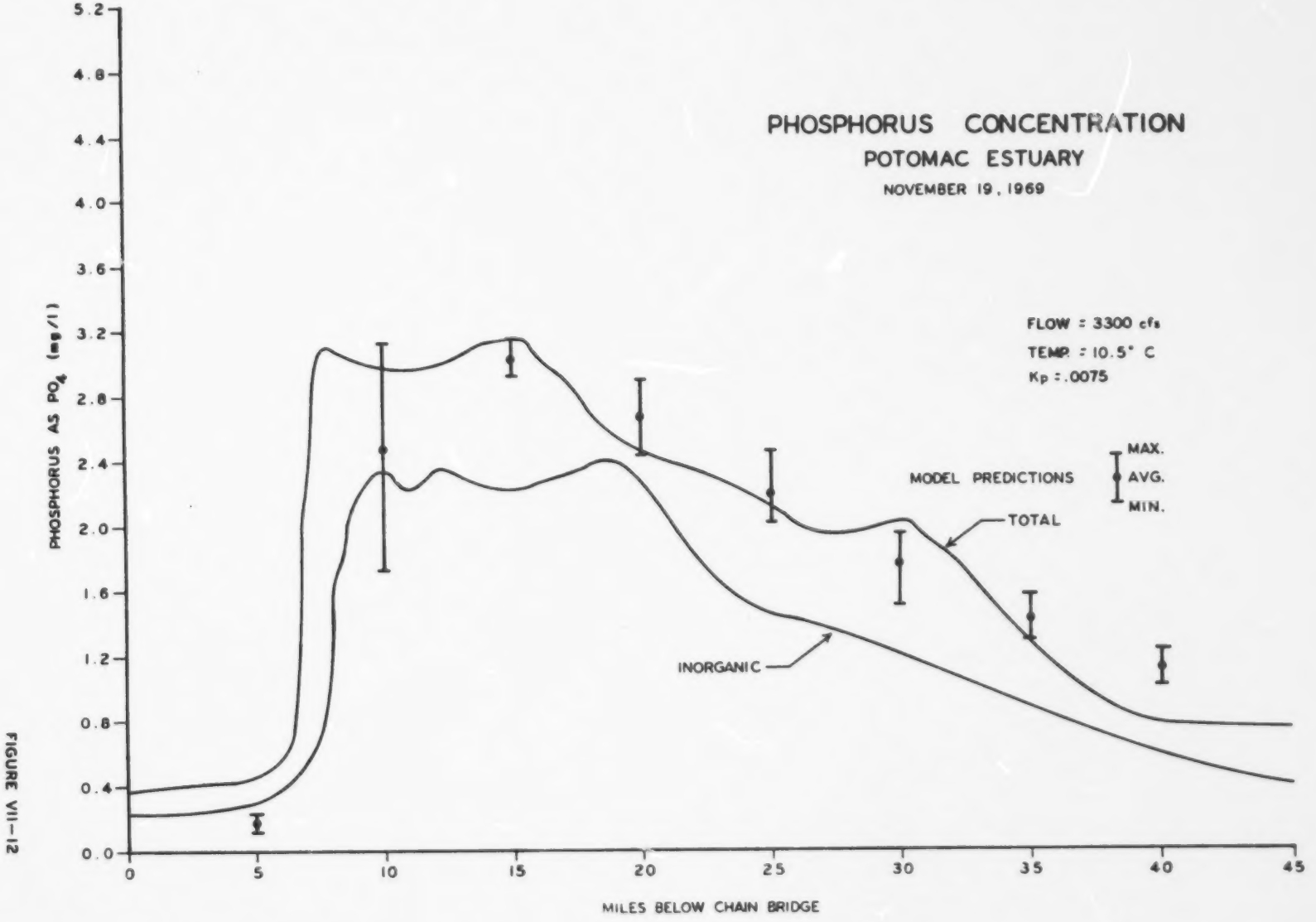
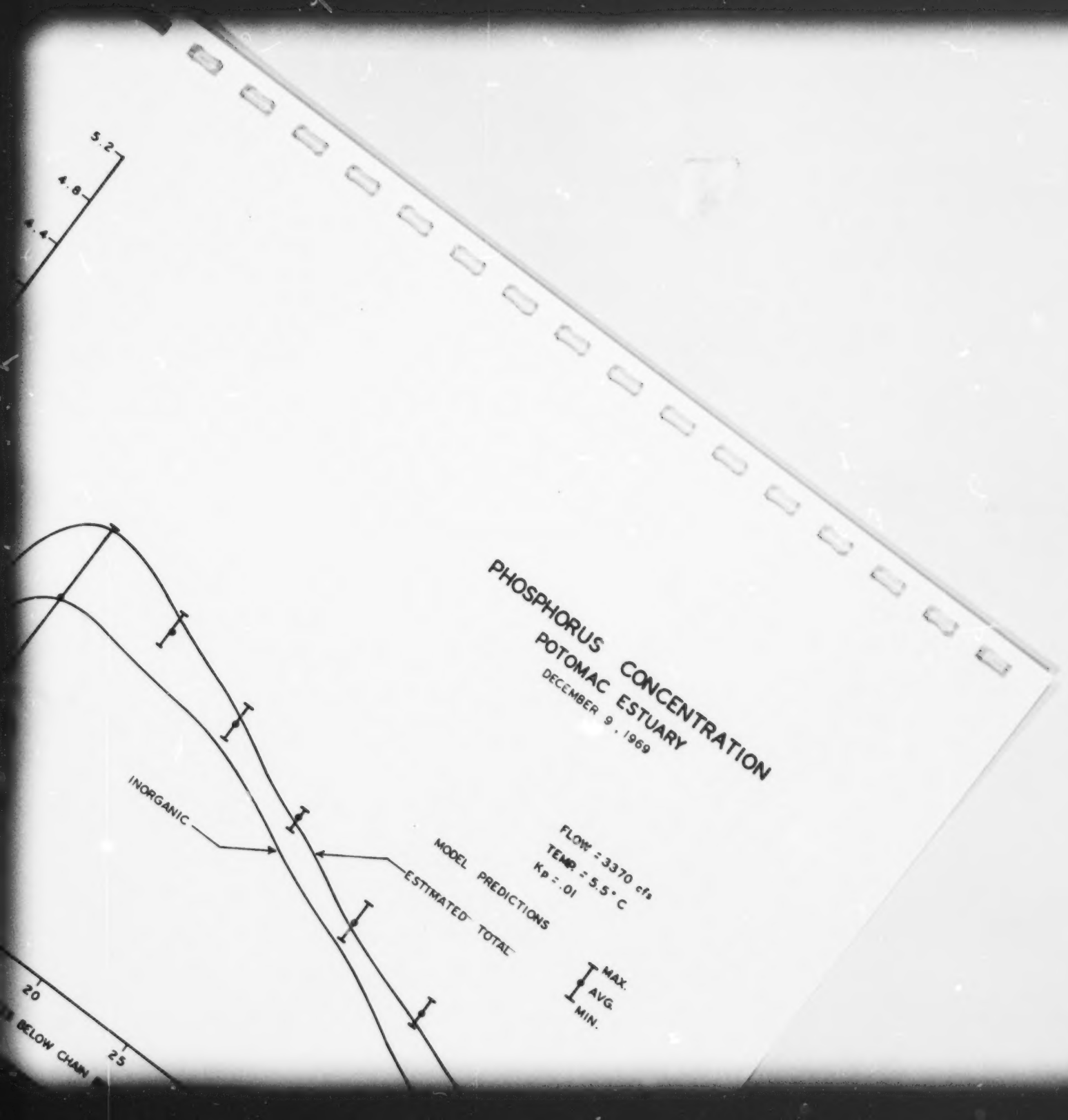


FIGURE VII-12


5.2
4.8
4.4
PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
DECEMBER 9, 1969
INORGANIC
MODEL PREDICTIONS
ESTIMATED TOTAL
FLOW = 3370 cfs
TEMP = 5.5° C
Kp = .01
MAX.
AVG.
MIN.
20
25
BELOW CHAIN

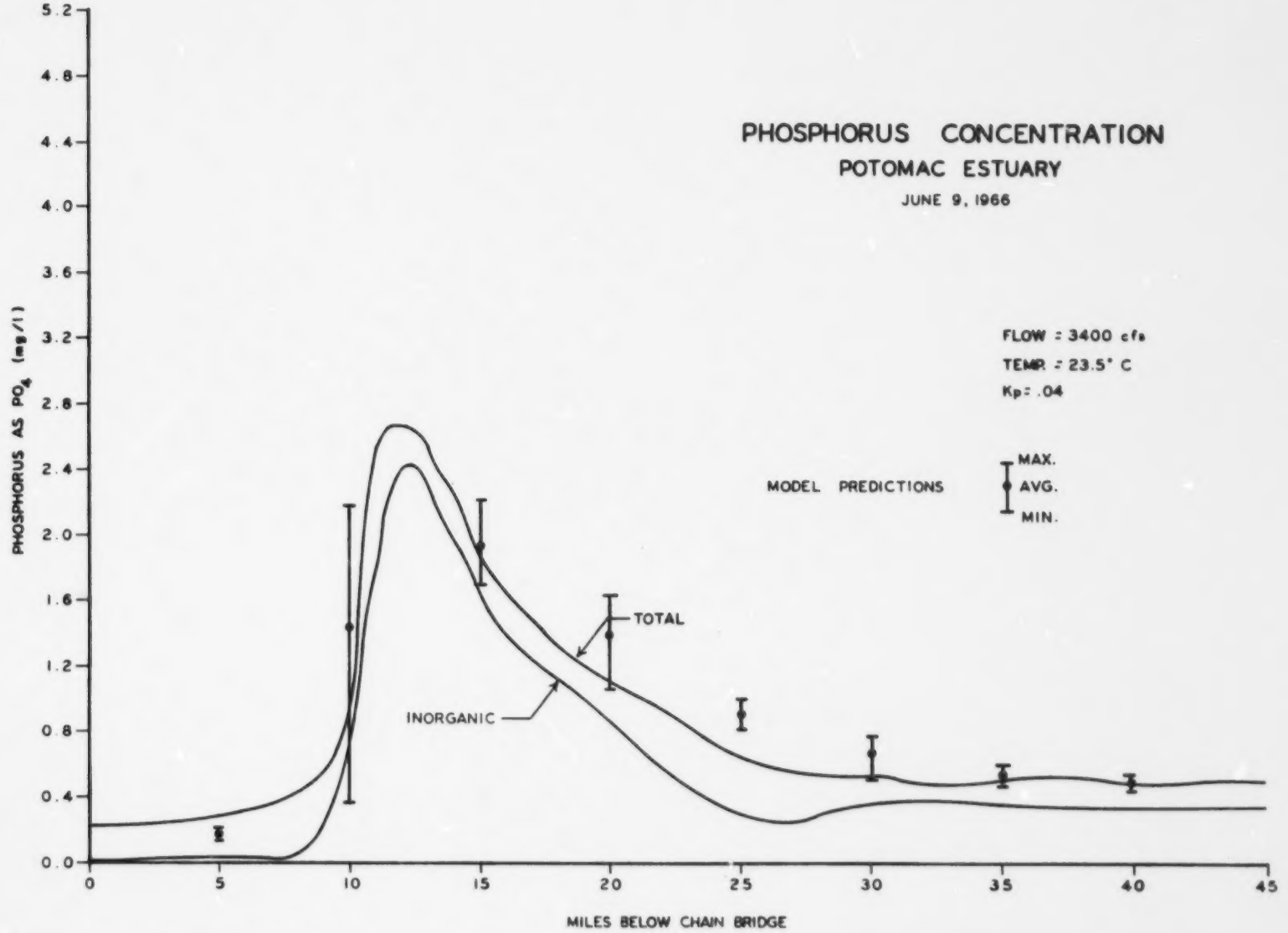


FIGURE VII-14

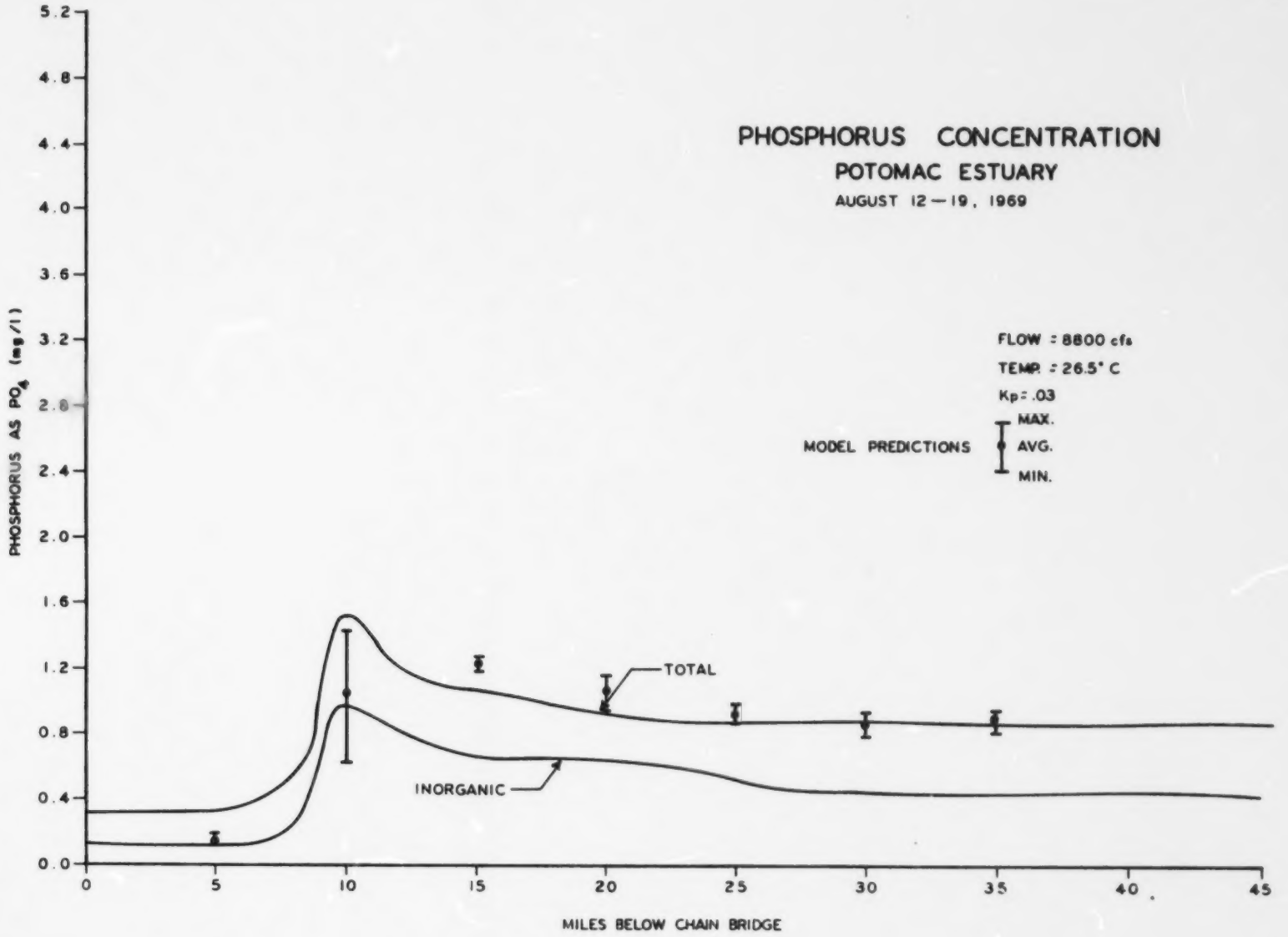


FIGURE VII-15

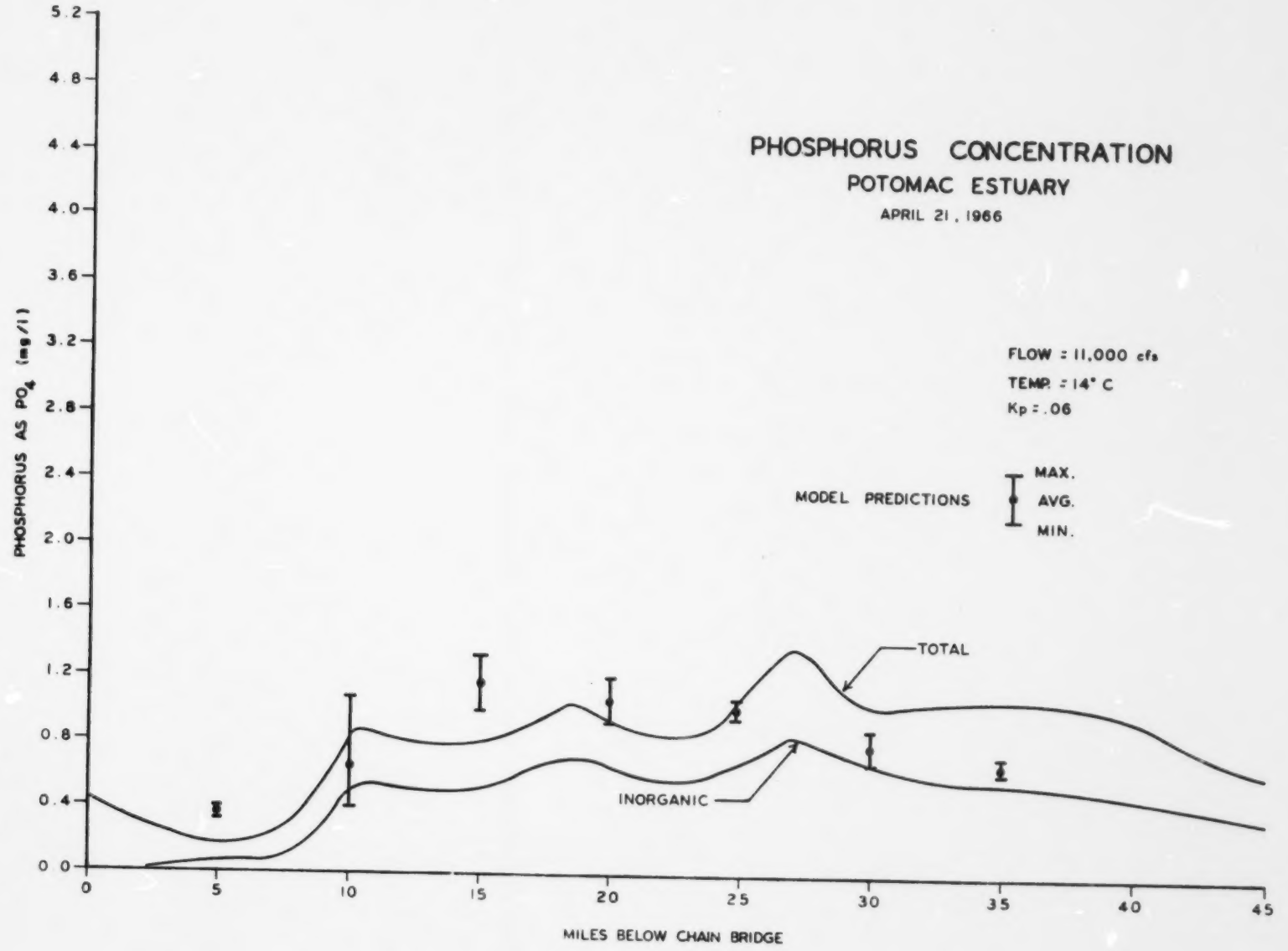


FIGURE VII-16

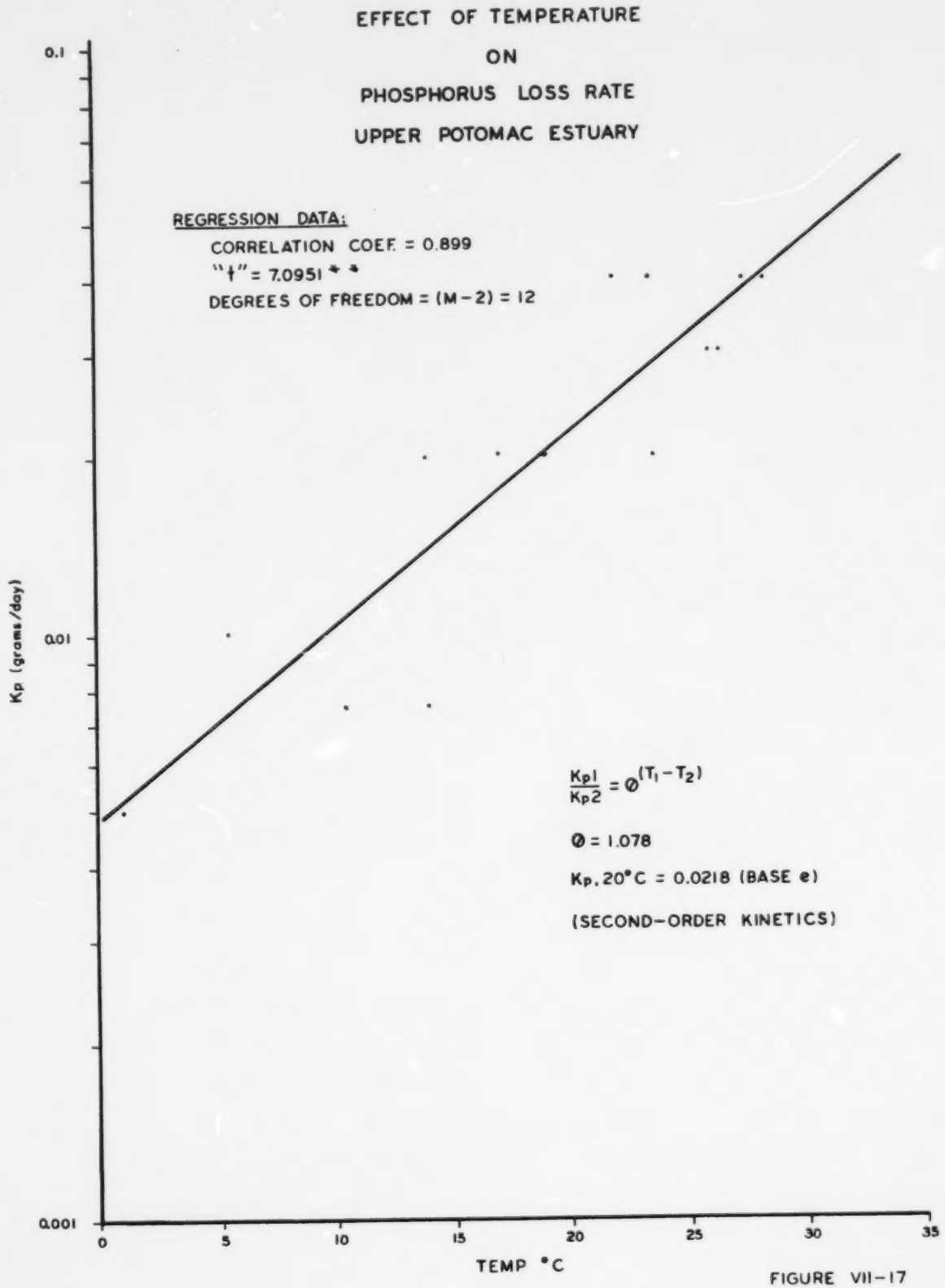


FIGURE VII-17

C. SIMULATION OF PHOSPHORUS TRANSPORT THROUGH AN ANNUAL CYCLE

The mass transport and spatial distribution of total phosphorus over an annual cycle must be known and predictable if the role of phosphorus in the eutrophication process and a management program for wastewater treatment are to be determined. Because of its importance, AFO endeavored to mathematically model phosphorus transport in the Potomac Estuary during a 15-month period in 1969 and 1970. This period was characterized by both high and low summer flows and offered an ideal situation for simulation. A modified version of the Thomann Model (DECS III) which incorporated second-order kinetics and the phosphorus loss rated developed in the preceding section was used for this simulation.

Observed and predicted phosphorus (TPO_4) data are shown for five selected stations in Figures VII-18 through VII-22. A comparison of the two profiles in each figure will indicate that the basic temporal distribution, including seasonal trends, was simulated reasonably well.

Some difficulty was experienced in simulating phosphorus under excessive algal productivity conditions. This problem can be evidenced in Figures VII-19 (Piscataway Creek), VII-20 (Indian Head) and VII-21 (Maryland Point). In order to improve the predictive capability of the model during these periods, such factors as the extent of phosphorus regeneration following the death of algal cells and the quantity of phosphorus exchange with the bottom sediments during different flow conditions would have to be quantitatively defined.

ANNUAL PHOSPHORUS PROFILES
POTOMAC ESTUARY AT HAINS POINT
1969-1970

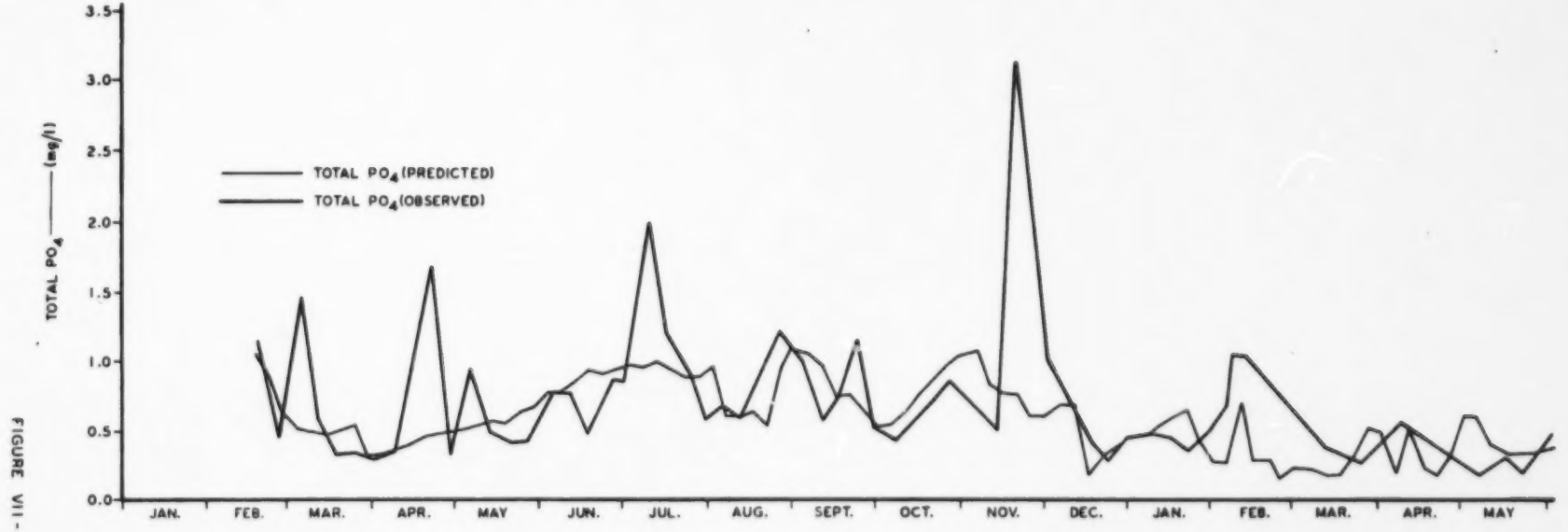


FIGURE VII - 18

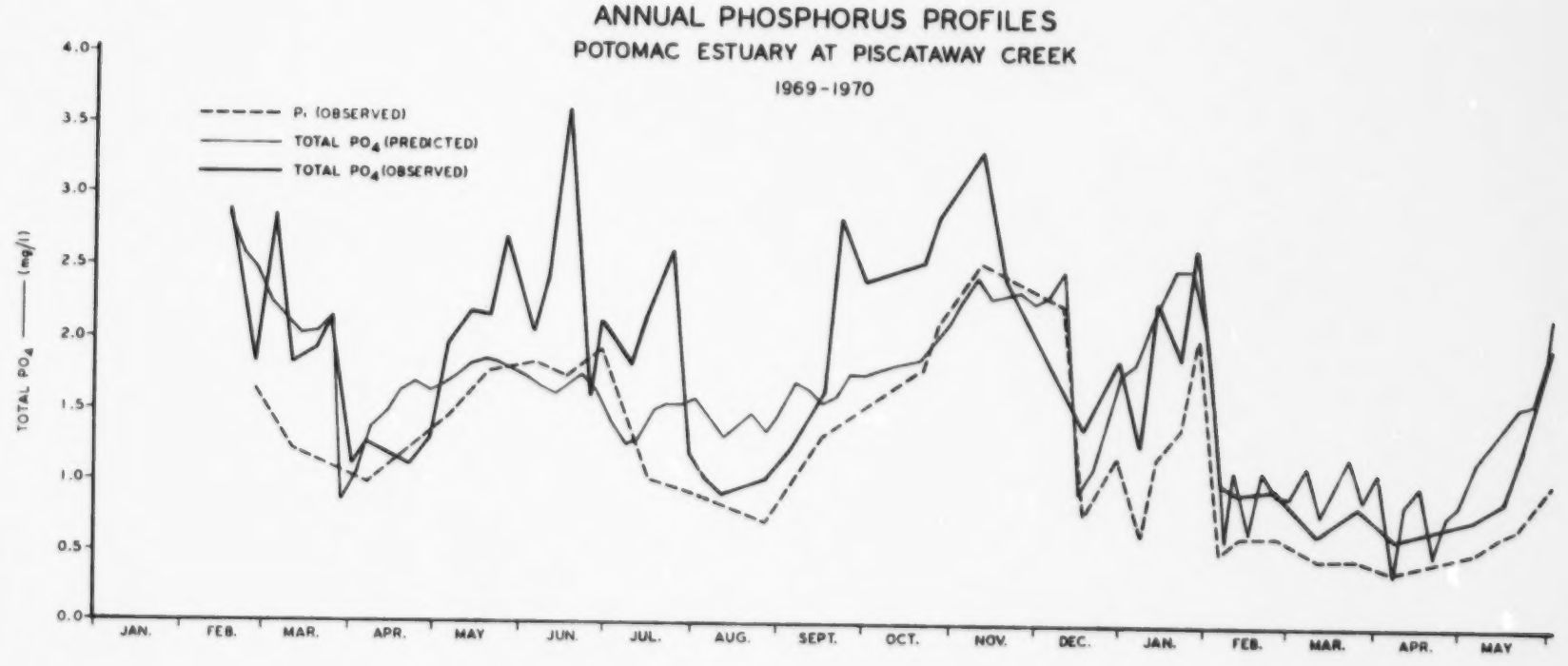


FIGURE VII-19

ANNUAL PHOSPHORUS PROFILES
POTOMAC ESTUARY AT INDIAN HEAD
1969-1970

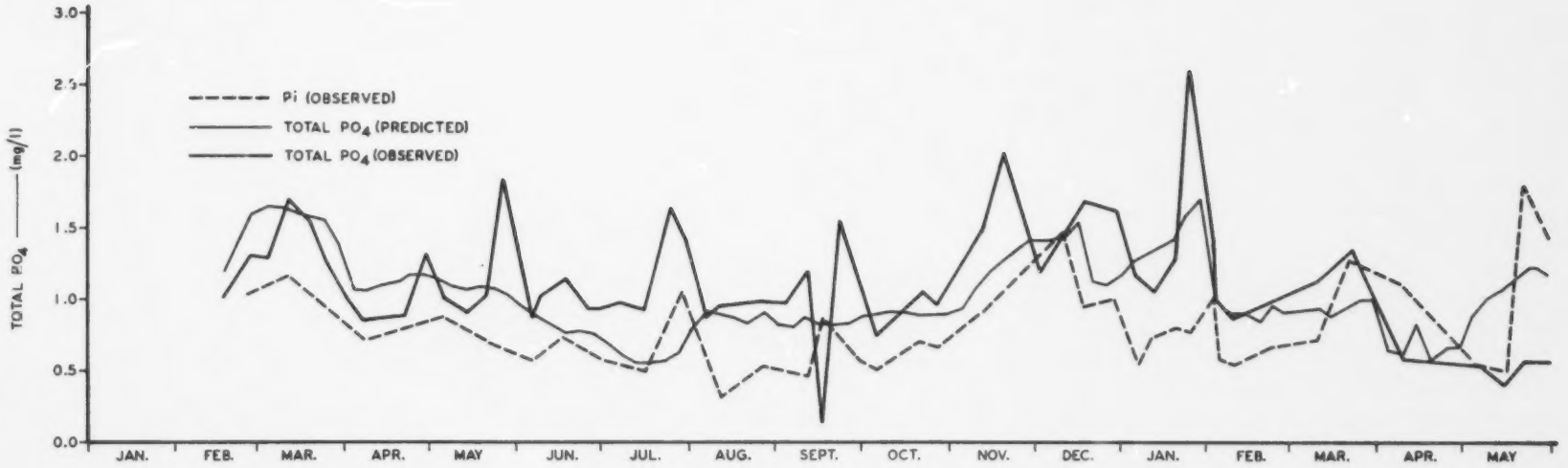


FIGURE VII-20

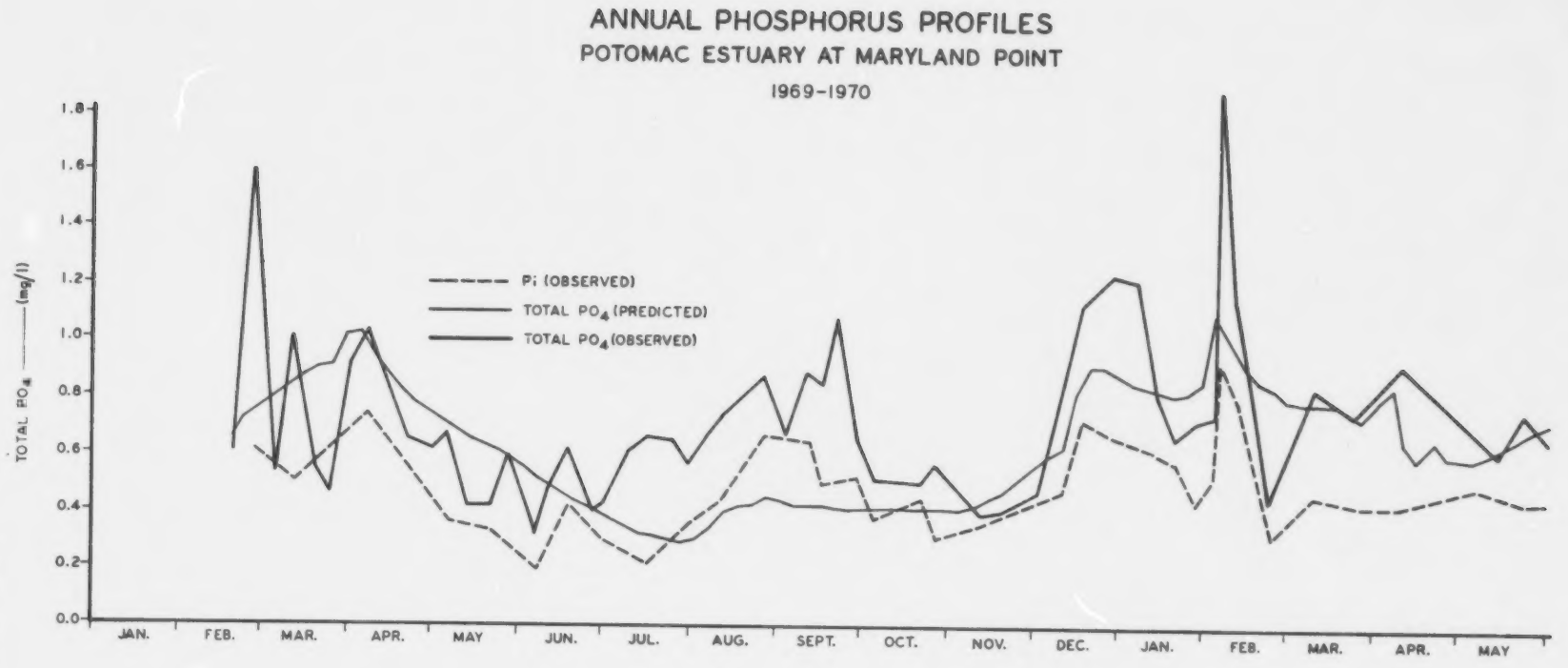


FIGURE VII-21

ANNUAL PHOSPHORUS PROFILES
POTOMAC ESTUARY AT PINEY POINT
1969-1970

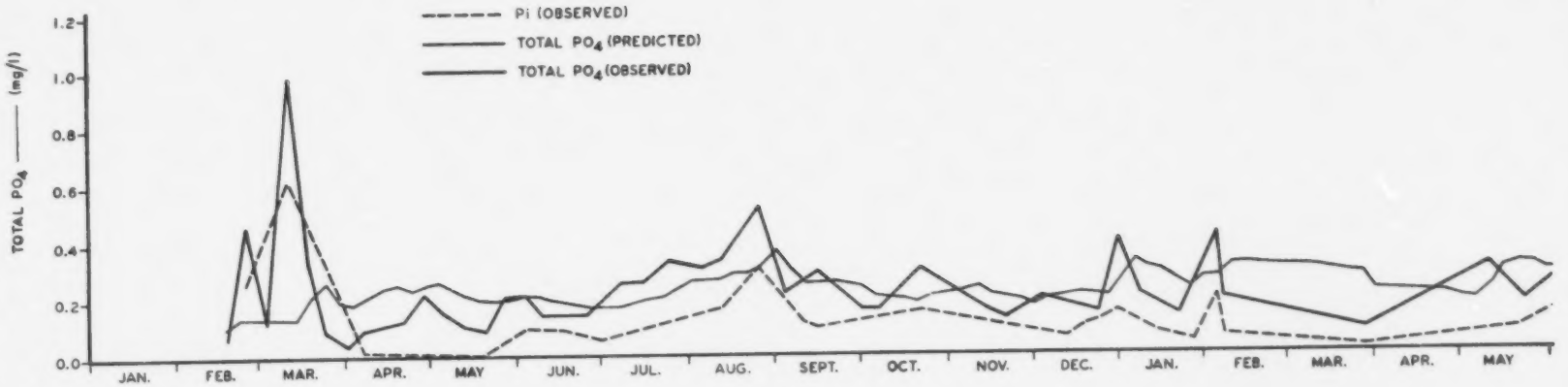


FIGURE VII-22

D. CHLOROPHYLL PREDICTIONS BASED ON PHOSPHORUS ASSIMILATION BY THE BIOMASS

To delineate that portion of the previously computed loss rate representing biological uptake of phosphorus by algal cells from other processes and to better understand the phosphorus contribution to eutrophic conditions in the Potomac Estuary, an attempt was made to predict chlorophyll levels based upon various phosphorus conversion or assimilation factors. A special version of the DEM that correlated algal production, as measured by chlorophyll a, with inorganic phosphorus uptake was used for simulation under four historical conditions. Mass relationships between the two were determined from algal chemical composition analysis.

Figures VII-23 to VII-26 show observed chlorophyll profiles and those obtained from the model assuming phosphorus conversion factors of (1) 10 percent, (2) 25 percent, (3) 50 percent, and (4) 75 percent. The data pertain to late summer and early fall periods during which freshwater flows varied from 185 to 2,200 cfs. As can be seen, the model predictions indicate that only about 10 to 20 percent of the phosphorus losses from the aqueous system can be accounted for by uptake of algal cells. Therefore, the remaining 80-90 percent must be associated with the deposition of phosphorus or some other physical process. Analyses of the bottom muds in the upper estuary further substantiate the fact that large quantities of phosphorus are indeed being lost to sediments.

Insofar as eutrophication is concerned, it appears that there is an abundance of phosphorus in the critical algal growing areas of the Potomac Estuary. Since the standing crop of blue-green algae was pre-

dicted from the nitrogen cycle, and only a 50 percent utilization of the available phosphorus produced excessive chlorophyll when compared to observed data, and for other reasons enumerated by Jaworski et al. [5], nitrogen is probably the growth-rate-limiting nutrient in the middle portion of the estuary at the present time. However, this presumption does not lessen the need to control phosphorus to the maximum extent possible, including loadings from wastewater treatment facilities, in the Potomac Estuary for several reasons: (1) the potential for controlling phosphorus is extremely great, especially during high flow periods (2) rapid phosphorus transport and mobility and uncertainty of its recycling ability and (3) phosphorus criteria for eutrophication control are considerably more stringent than nitrogen criteria for comparable reaches of the estuary.

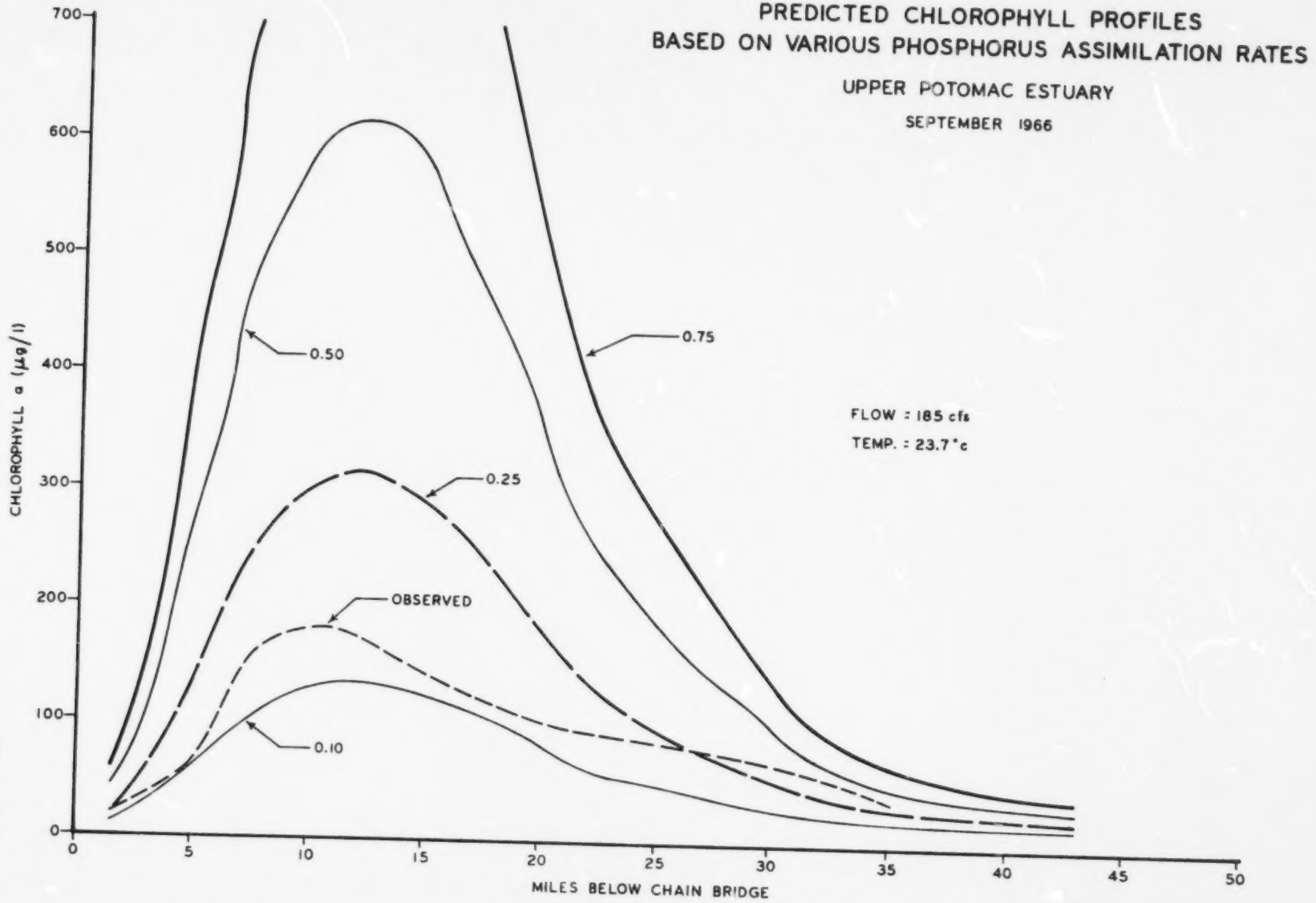


FIGURE VII-23

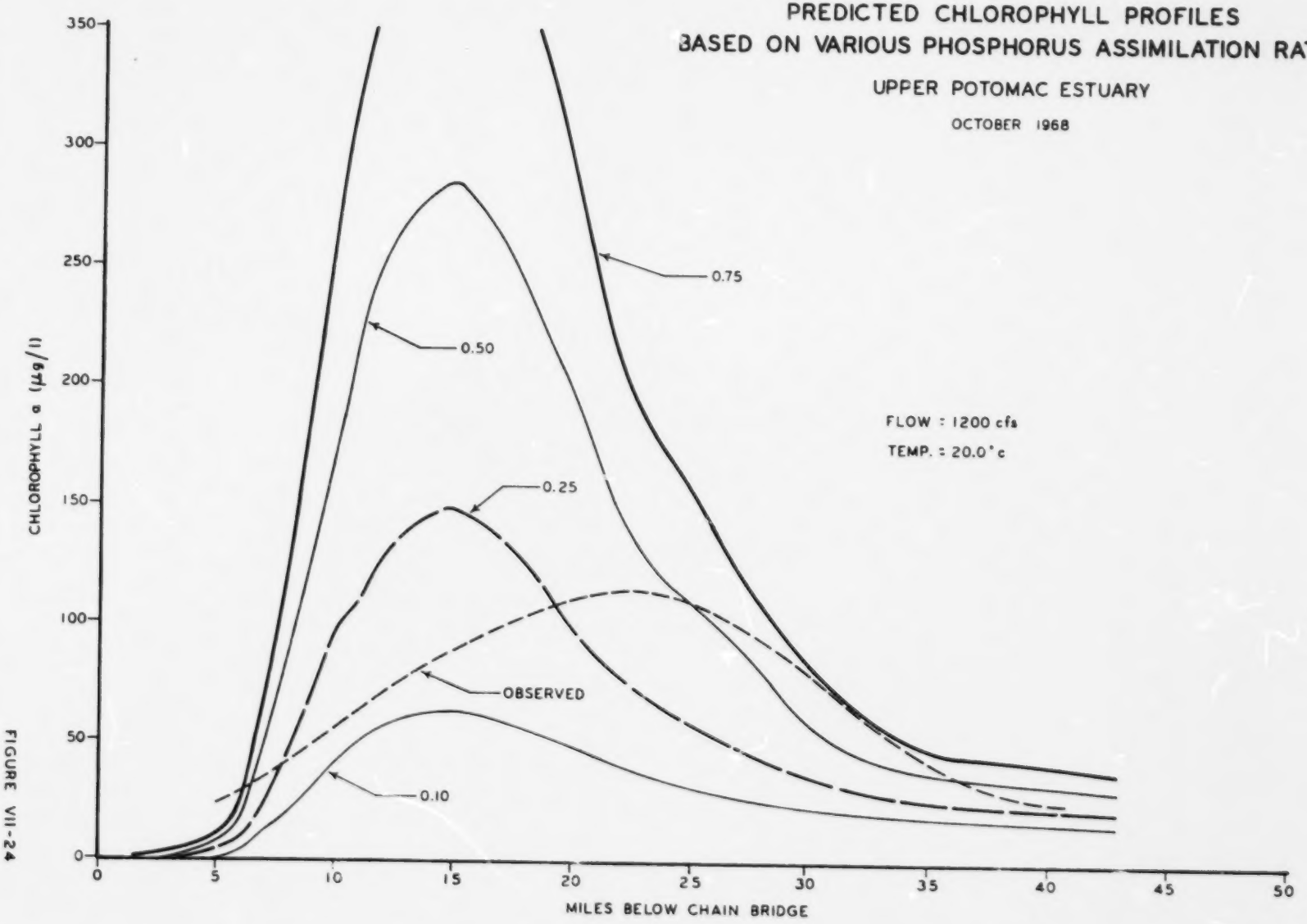


FIGURE VII-24

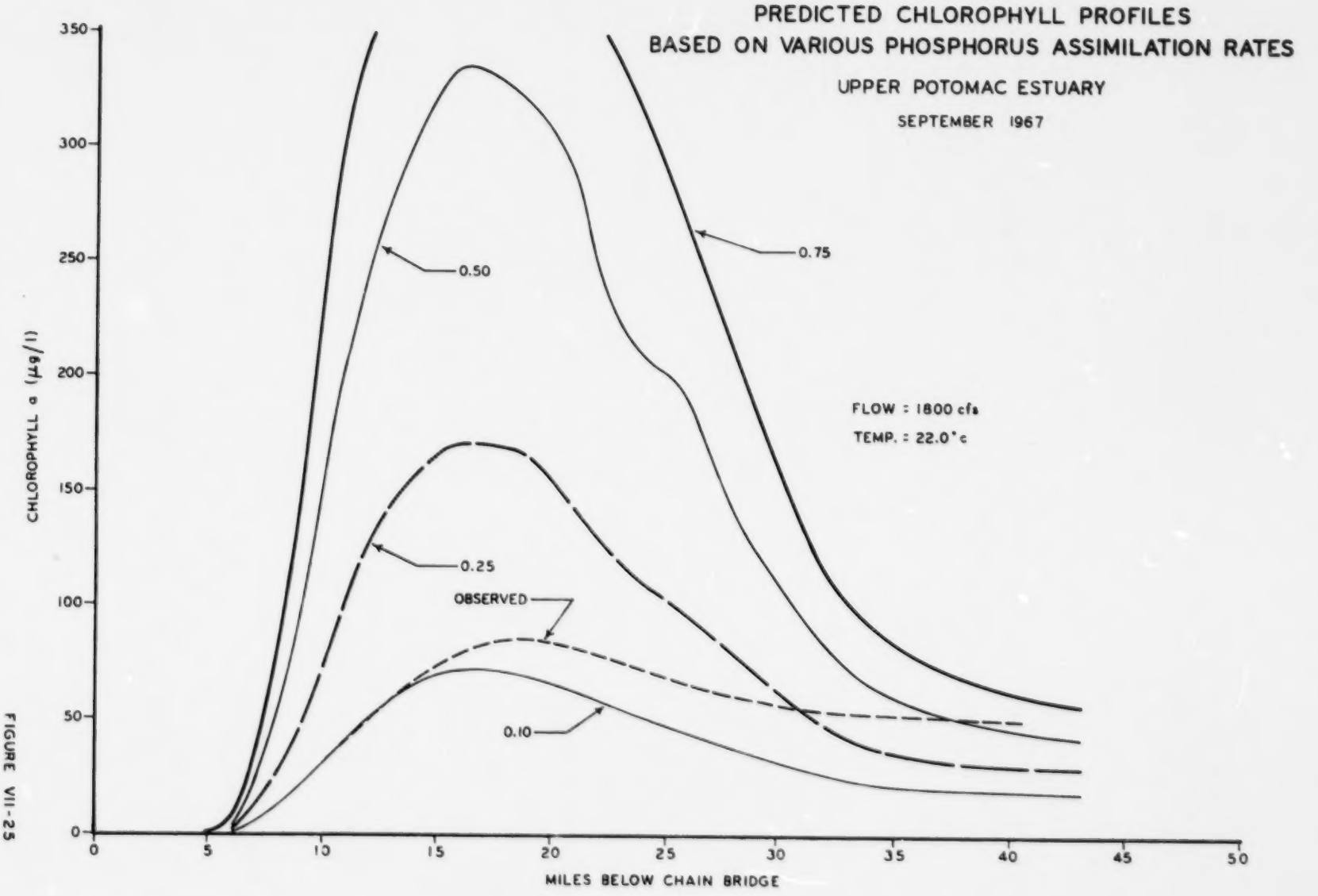


FIGURE VII-25

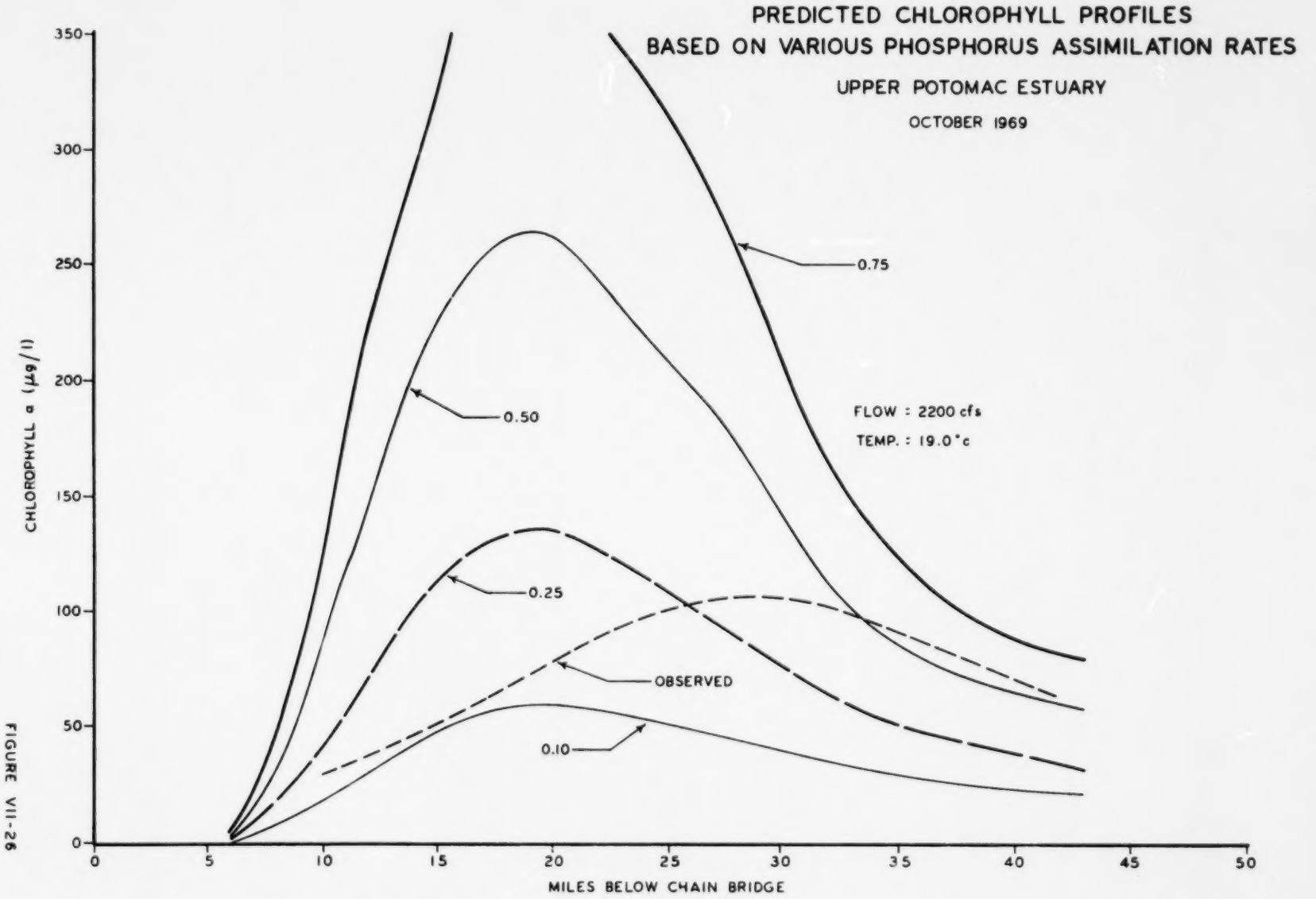


FIGURE VII-26

CHAPTER VIII

DISSOLVED OXYGEN BUDGET

A. FORMULATION OF SOURCES AND SINKS

A schematic diagram of the dissolved oxygen budget incorporated in the AFO mathematical model of the Potomac Estuary is shown in Figure V-3. As can be seen, the model consisted of the following five linkages:

1. Oxidation of carbonaceous matter,
2. Oxidation of nitrogenous matter (ammonia and organic nitrogen),
3. Oxygen production and respiration of simulated algal standing crops based upon the nitrogen cycle,
4. Benthic demand, and
5. Atmospheric reaeration.

One important limitation of the DO model presented above is that it neglected the oxygen demand of dying and decomposing algae. An effect such as this may be included relatively easily by regenerating the oxidizable carbon and nitrogen "tied-up" in plant cells and was considered in a subsequent version of the model discussed later in this report. Although this DO sink may be significant in the fall months when algal death is prevalent, the extremely low chlorophyll decay rates required for most model verification runs (Chapter VI) and the apparent success of the existing model in simulating various DO conditions

estimate the oxygen production and respiration rates for a known standing crop of algae. The data collected during this survey are shown in Table VIII-1. A considerable amount of data relating to light penetration (Secchi Disk) was available for the entire Potomac Estuary. The assumed depth of the euphotic zone was based upon an analysis of this data. Finally, a benthic respirometer was used by AFO in the upper estuary to obtain benthic oxygen demand rates. These data, which are shown in Figure VIII-1, indicate that benthic uptake rates vary spatially, with the maximum rate occurring near the District of Columbia's Blue Plains Sewage Treatment Plant (River Mile 10.4).

Table VIII-1

OXYGEN PRODUCTION AND RESPIRATION RATE SURVEY
Upper and Middle Potomac Estuary
1970

Date	Water Temp. (°C)	Chlorophyll a Range (µg/l)	Light Intensity Range (foot candles)	Oxygen Production mg/hr/µg of Chlorophyll a	Respiration mg/hr/µg of Chlorophyll a
6-22	26	40-110	250-300	.0073	.0023
6-23	27	70-120	200-300	.0084	.0011
6-24	27	54-110	200-300	.0087	.0024
6-25	27	50-60	200-300	.0121	.0033
7-20	28	30-100	250-400	.0130	.0022
7-21	27	30-143	200-300	.0130	.0016
7-22	26	30-140	100-200	.0146	.0017
7-27	28	-	-	.0060	.0010

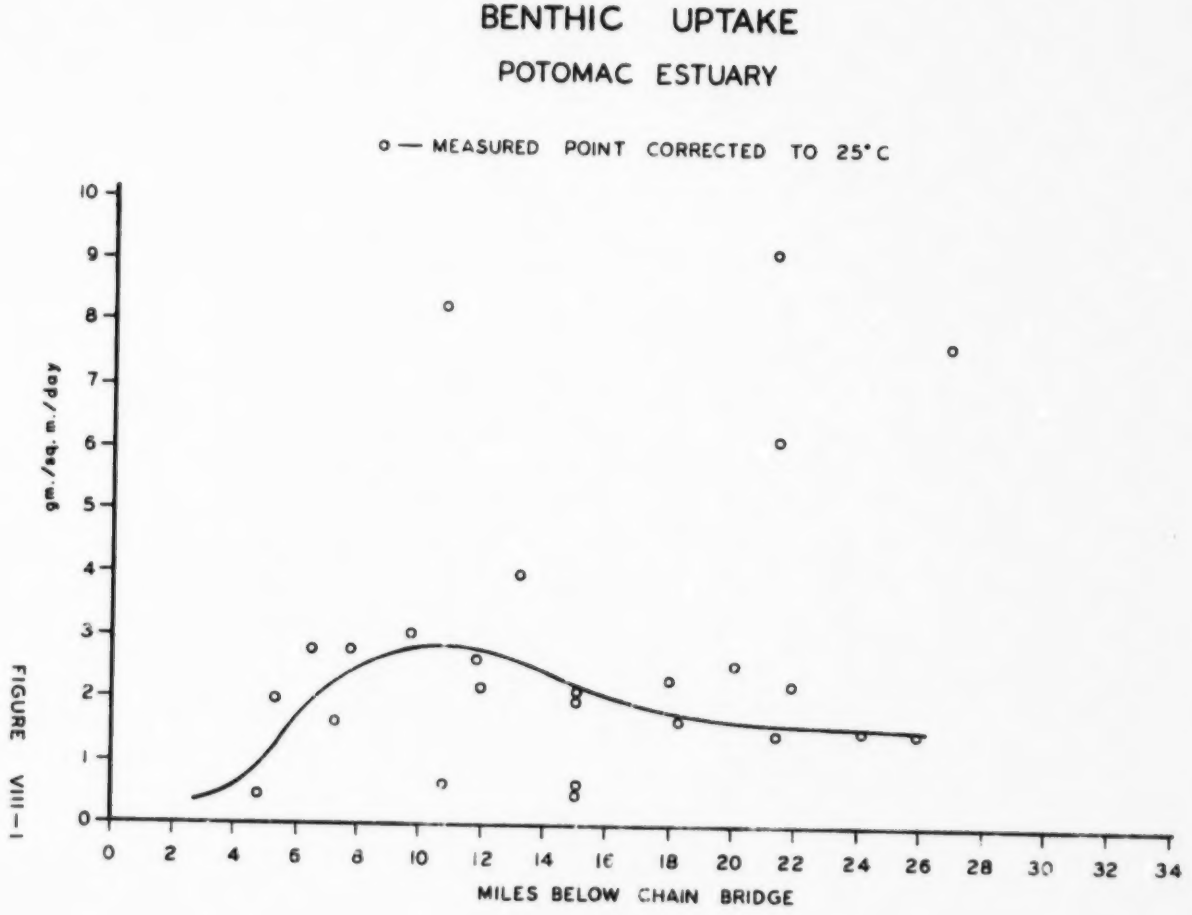


FIGURE VIII—1

B. SIMULATION AND MODEL VERIFICATION STUDIES

Eight separate intensive sampling runs conducted in the upper Potomac Estuary between 1965 and 1969 were used, initially, to verify the DO budget model, including the various reaction rates and assumptions presented in the previous section. Each run represented approximately a 20- to 30-day period under relatively steady-state conditions. The flows for the eight sets of sampling data ranged from 185 cfs to 8,800 cfs.

Figures VIII-2 through VIII-9 show the observed DO profiles and those predicted by the mathematical model. As can be seen, favorable agreement was obtained in every case. Although the two sets of profiles did not coincide exactly, the magnitude and location of the critical DO deficit and the general rate of depression and recovery appeared to be simulated reasonably well using the aforementioned coefficients. The critical deficit was primarily the result of the oxidation of carbonaceous and nitrogenous material in the wastewater effluents; the rate and extent of DO recovery was influenced greatly by the net effect of algal photosynthesis and respiration.

The pronounced decrease in DO predicted by the model in the extreme upper portion of the estuary during lower flow periods could have been due to the very deep holes in this area, which lowered the reaeration capacity and magnified the effects of algal respiration.

As a further test of the model's capability to predict dissolved oxygen distribution in the Potomac Estuary, a completely independent

and more recent (September 1970) condition was simulated. The sampling data collected by AFO on September 9, served to define the initial conditions. Data collected 20 days later and compared to model predictions after a comparable time period were used as a basis for verification.

The freshwater flow during this period ranged from 1,200 cfs to 1,900 cfs (1,500 cfs average), and the reaction rates and assumptions incorporated in the other eight runs were applied without change. The results of this simulation are shown in Figure VIII-10. Generally, good agreement was obtained between observed and predicted data describing the rate of oxygen depletion, the magnitude and location of the critical deficit, and the initial stage of recovery. The considerable divergence in the later stages of recovery may be ascribed to the extensive algal death and decomposition which normally occurs in that area of the estuary during late September. As stated previously the additional oxygen demanding load resulting from the biological decay of algal cells and nutrient regeneration had not been incorporated into this version of the model, and consequently, the secondary DO depressions that at times exist in the Potomac Estuary were not accurately simulated.

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

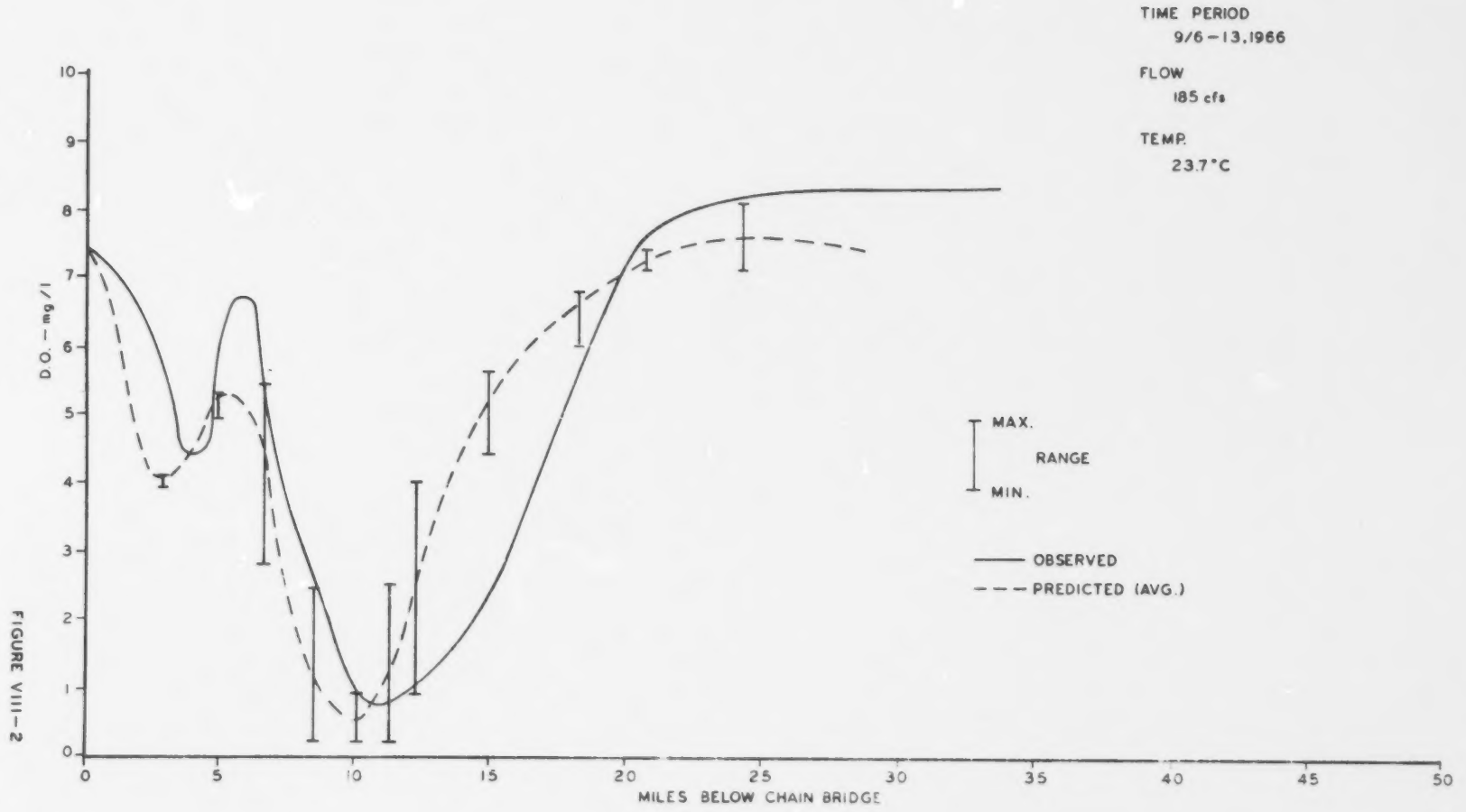


FIGURE VIII-2

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

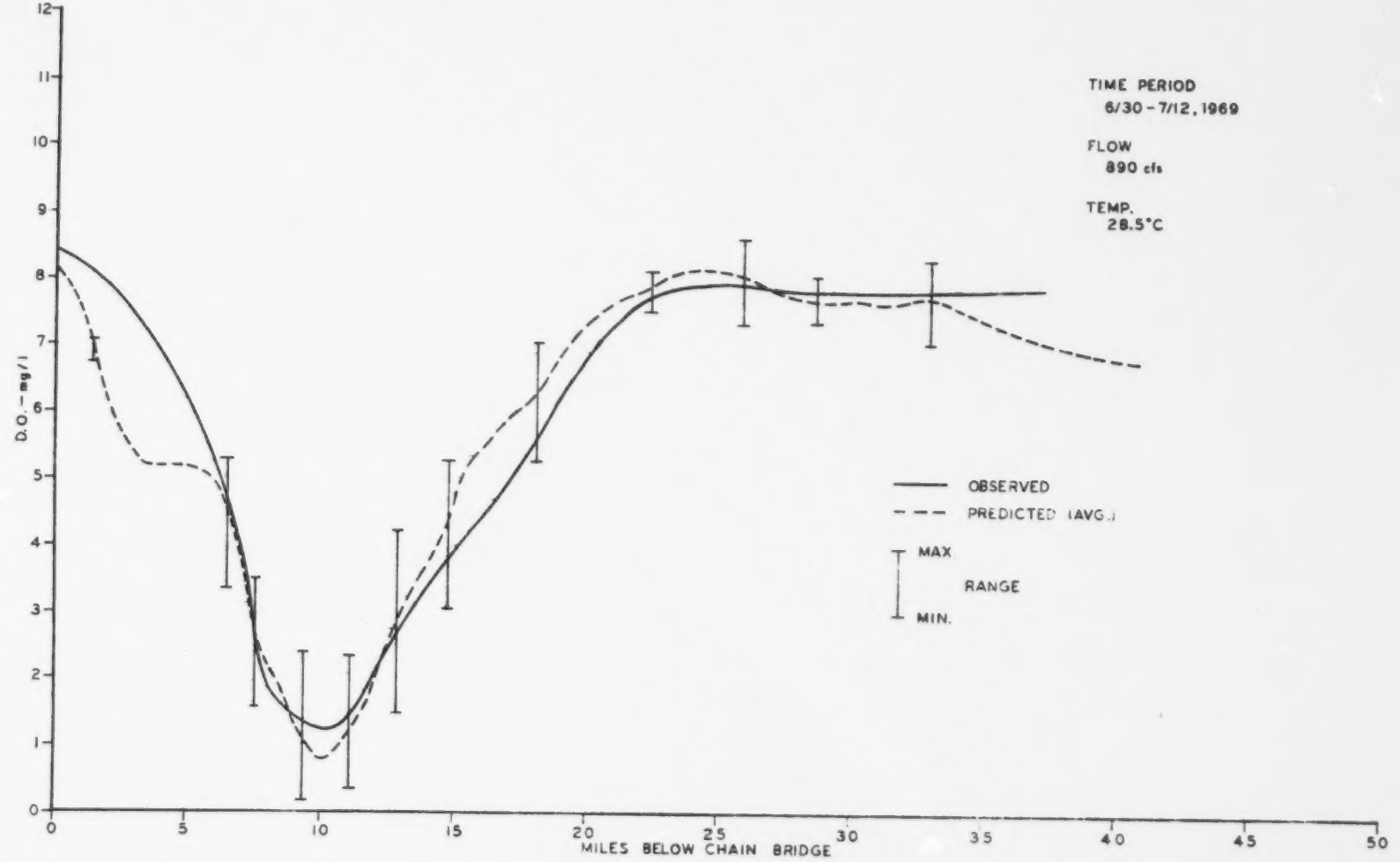


FIGURE VIII-3

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

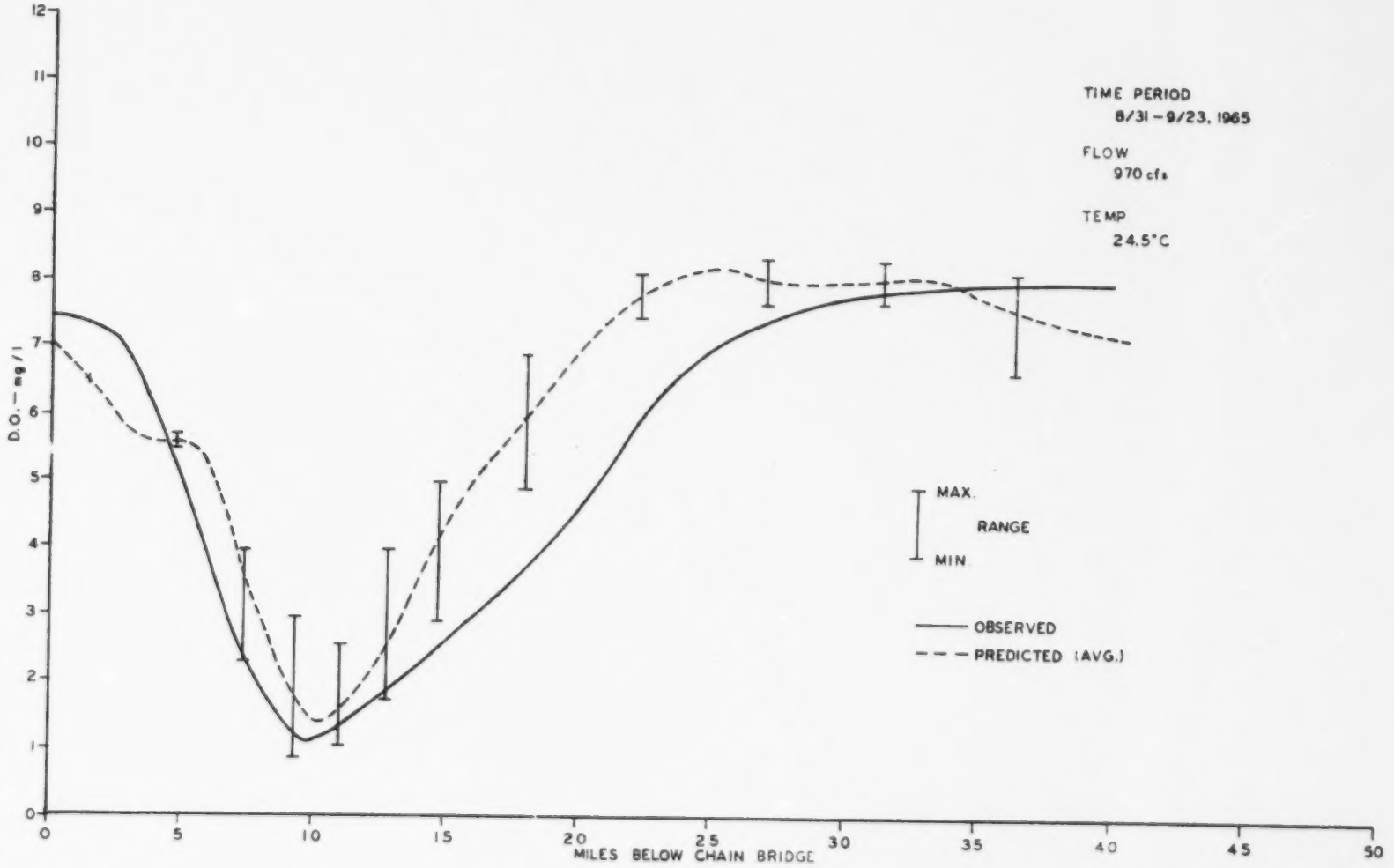


FIGURE VIII – 4

DISSOLVED OXYGEN PROFILES
UPPER POTOMAC ESTUARY

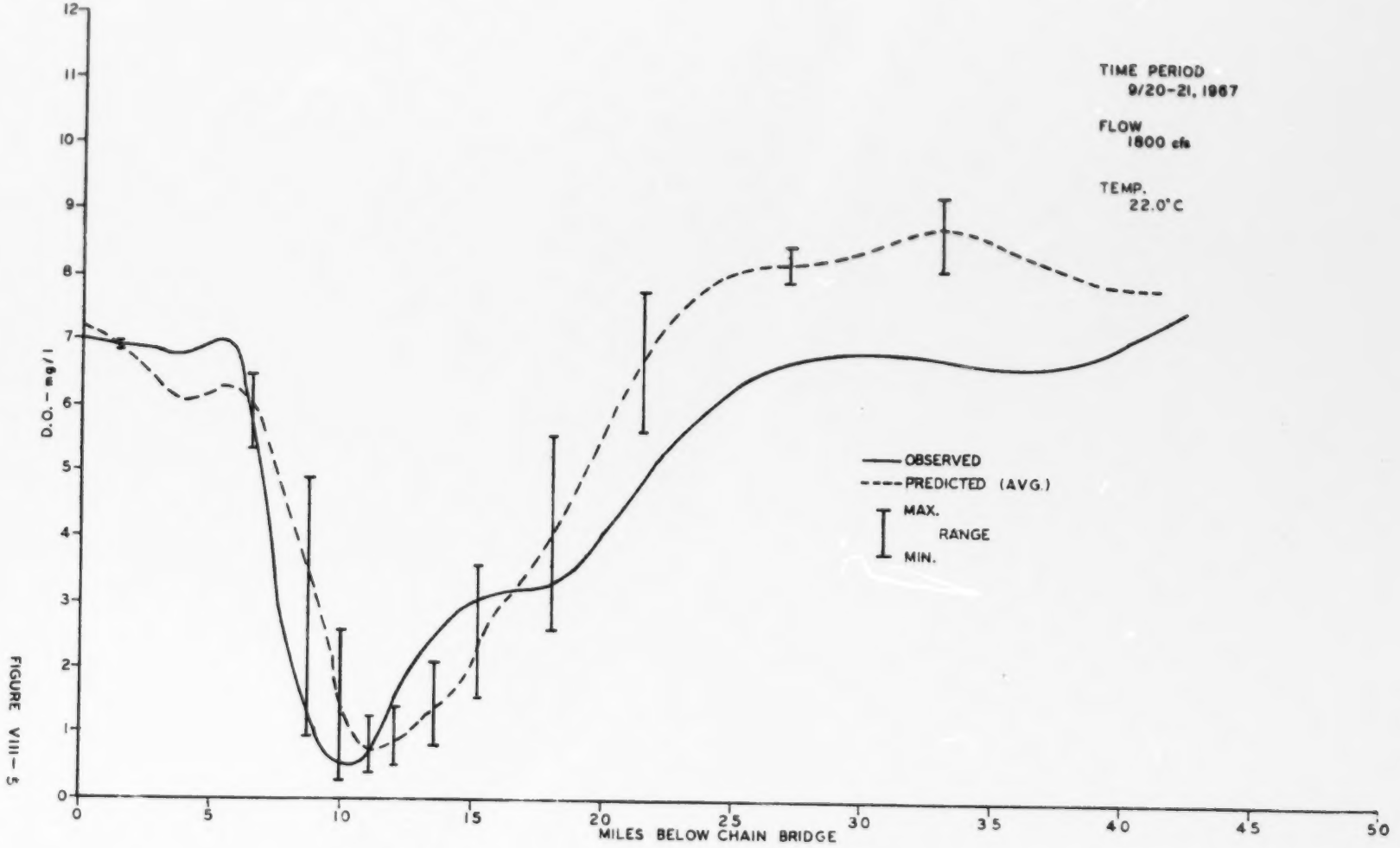


FIGURE VIII-5

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

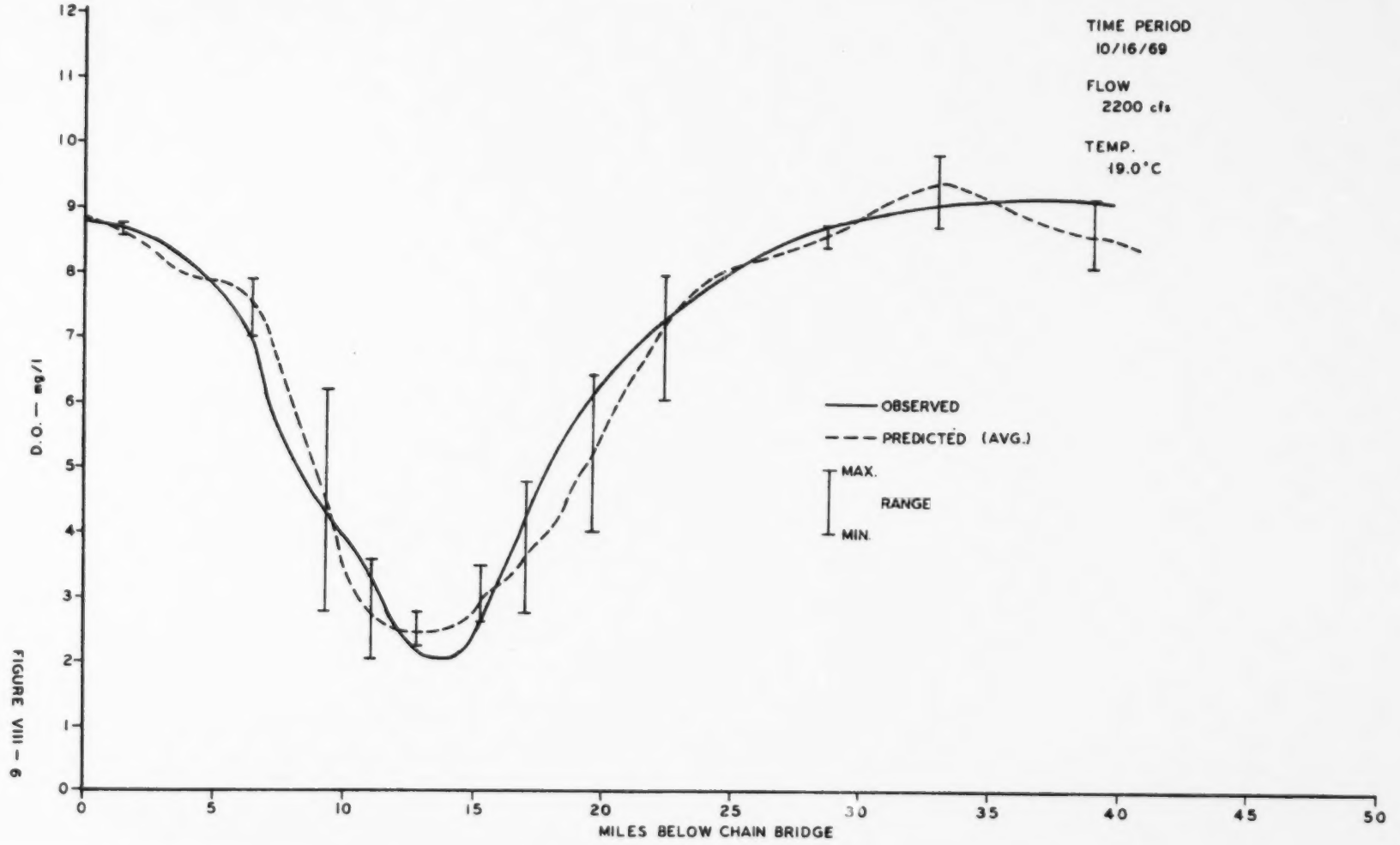


FIGURE VIII – 6

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

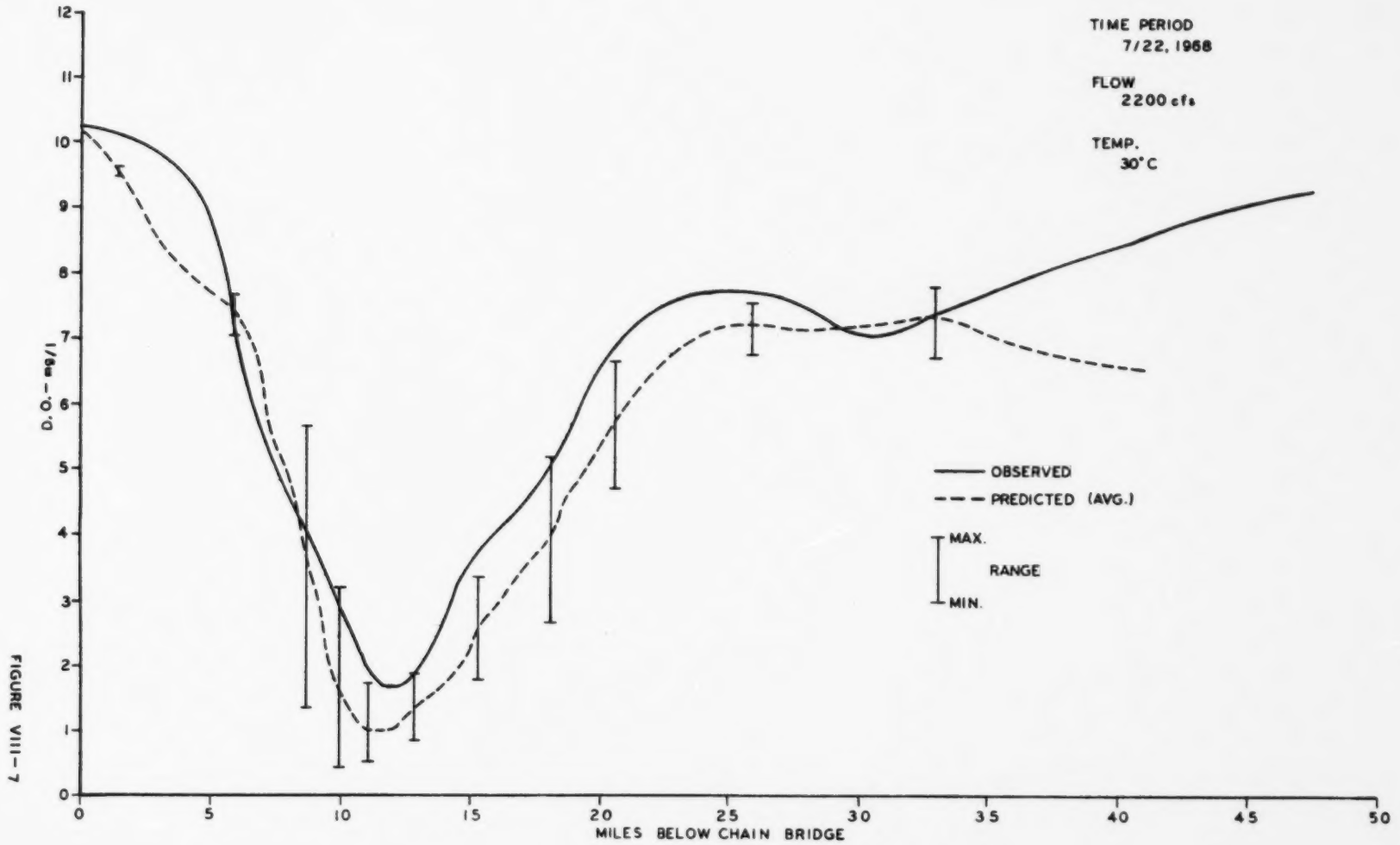


FIGURE VIII-7

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

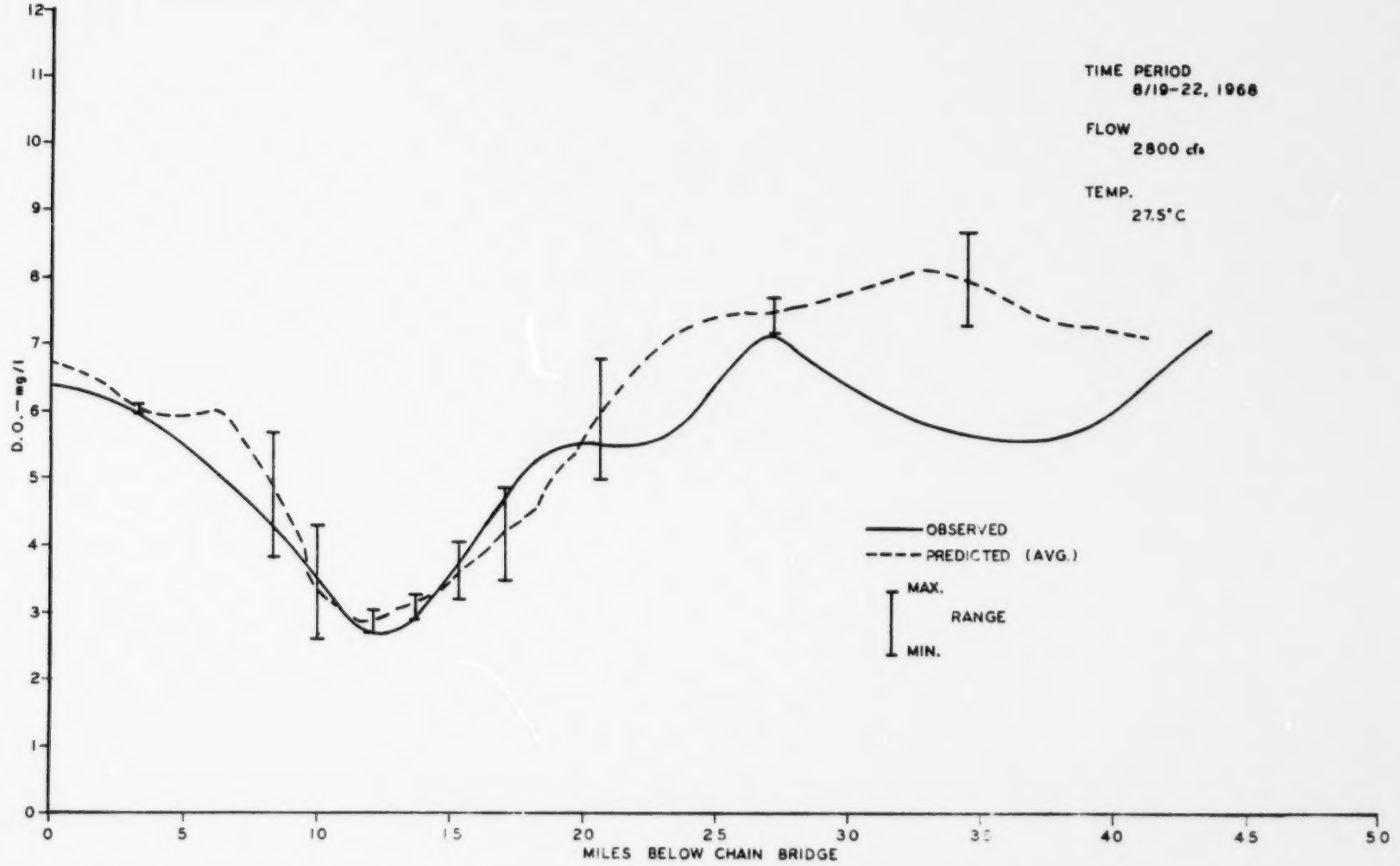


FIGURE VIII-8

DISSOLVED OXYGEN PROFILES
UPPER POTOMAC ESTUARY

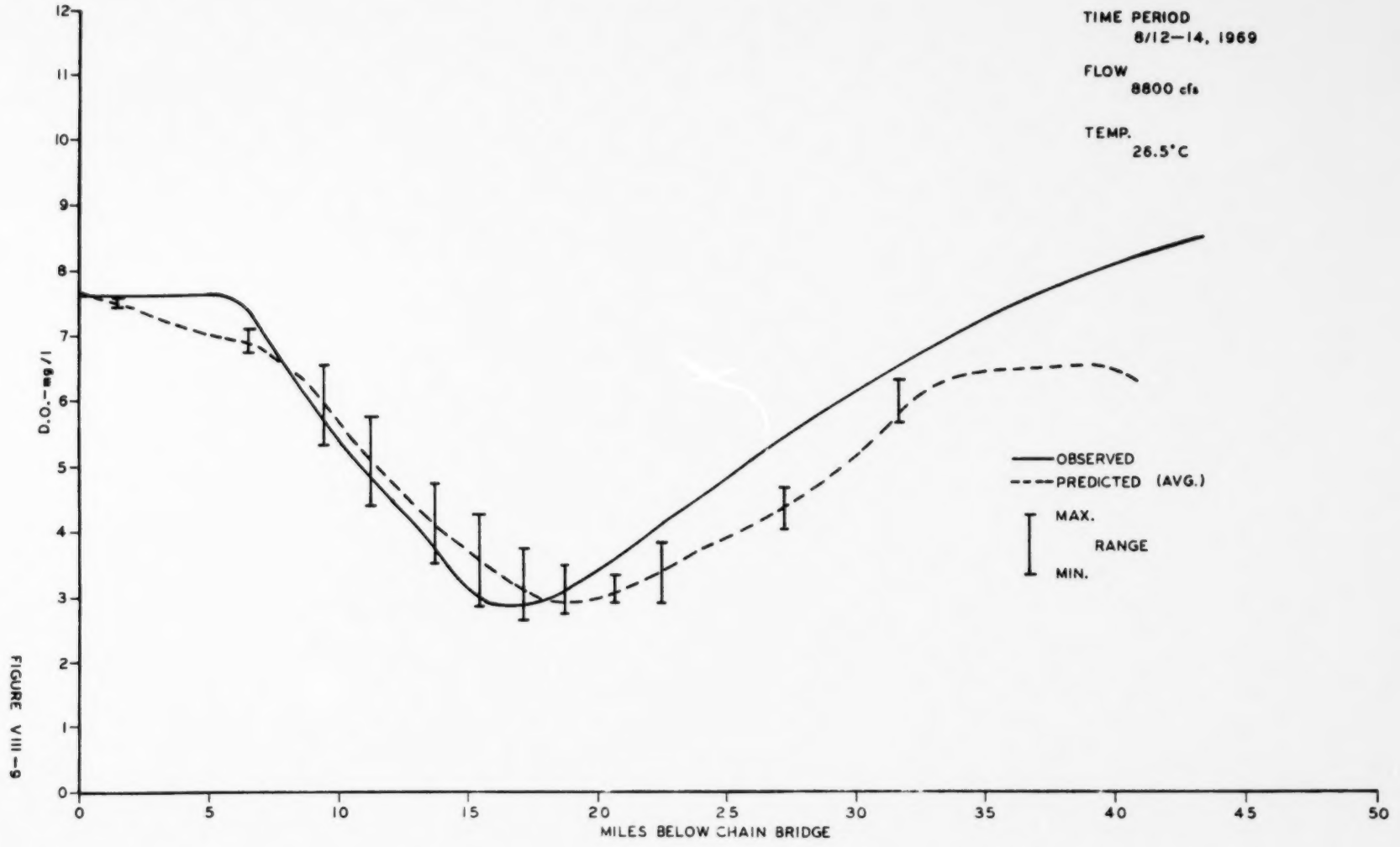


FIGURE VIII-9

DISSOLVED OXYGEN PROFILES

UPPER POTOMAC ESTUARY

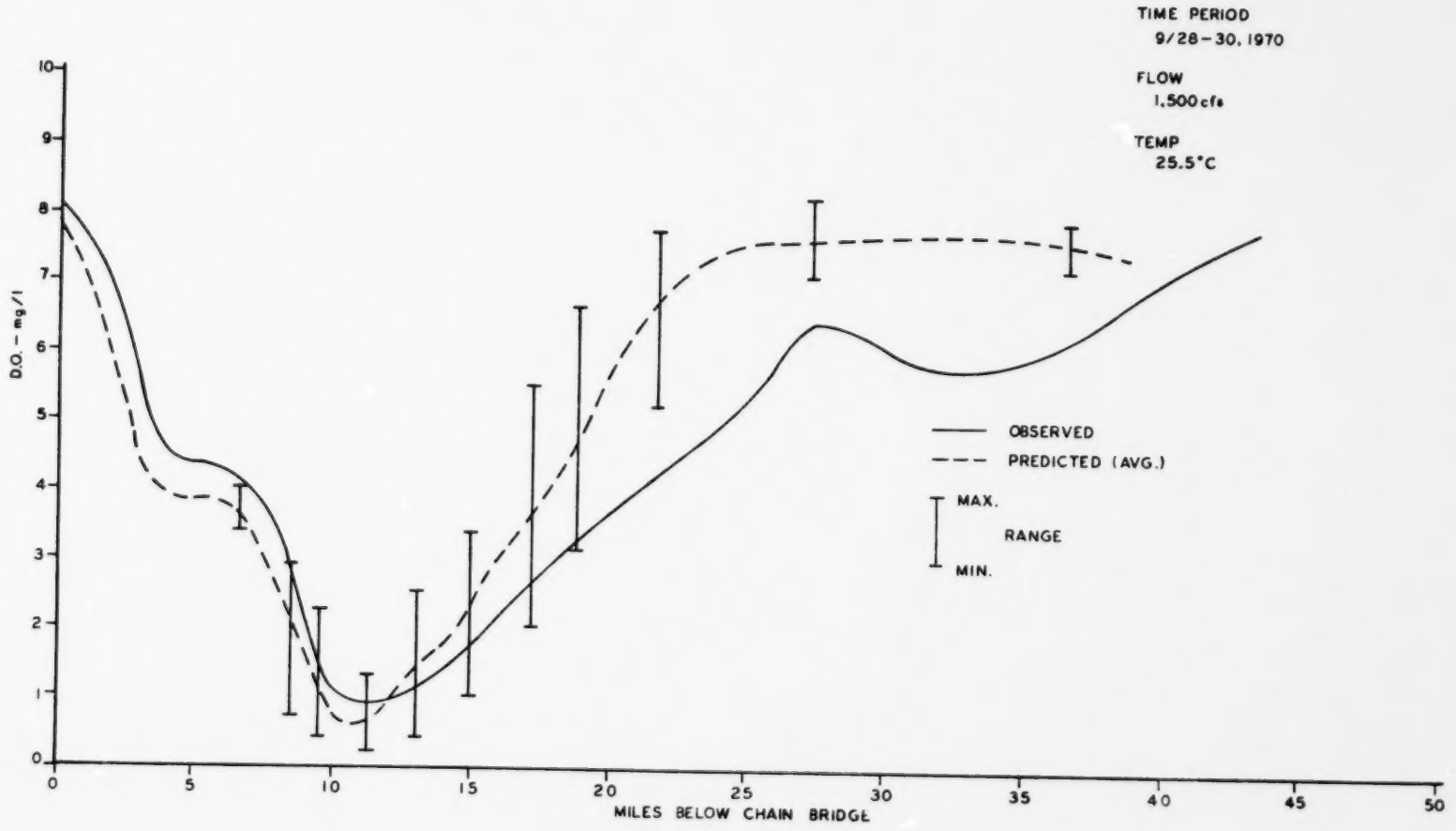


FIGURE VIII-10

C. SENSITIVITY ANALYSIS

A study was performed to determine the Potomac Estuary DO model's sensitivity to the various input rates. A knowledge of the relative importance of each rate in the DO budget offers assistance for (1) model verification, (2) the design of field and laboratory studies to define a particular rate by suggesting the necessary degree of accuracy required, and (3) the relation of the gross effect of each rate to the estuary's physical and biological parameters such as depth, surface area, and algal productivity.

The general approach adopted in this sensitivity analysis was to assume two values for each rate--one approximately one-half and the other twice the verified value. All of the model runs simulated the October 1969 loading condition that had been previously verified.

1. Effects of Oxidation Rates (Carbon and Nitrogen)

The simulated DO profiles based on carbonaceous and nitrogenous oxidation rates of 0.1/day and 0.3/day are shown in Figures VIII-11 and VIII-12. Figure VIII-11 illustrates the considerable effect that the carbonaceous rate exerts on the DO distribution, and in particular on the magnitude of the maximum deficit. Increasing the oxidation rate threefold results in a lowering of the critical sag point from 4.0 mg/l to 0.2 mg/l.

A comparison of Figures VIII-11 and VIII-12 clearly shows that the DO model is markedly less sensitive to the rate of nitrogenous oxidation than to the carbonaceous rate. A variation in K_n comparable to

that of K_c produced a change in the critical DO deficit of only about 1.0 mg/l. The reason for this difference in model sensitivity can be attributed to the greater masses of carbon in the system, and hence a greater range in the amount of oxidized material and DO demand for a given range in rates.

2. Effects of Photosynthesis and Respiration Rates

The effects of changing the algal photosynthesis or respiration rates in the DO model are quite extreme, particularly in the recovery region of the upper Potomac Estuary where algal growth is usually excessive. As shown in Figures VIII-13 and VIII-14, the model predictions behaved similarly when either the photosynthesis rate was increased or the respiration rate was decreased.

According to the DO profiles in Figure VIII-13, increasing the rate of photosynthesis fourfold, from 0.006 to 0.024 mg O_2/hr/µg chlorophyll, increased the critical sag point by 4.0 mg/l and greatly accelerated the rate and degree of DO recovery. Figure VIII-14 shows a similar occurrence when the respiration rate was lowered from 0.0016 to 0.0004 mg O_2/hr/µg chlorophyll. It should be noted that the maximum chlorophyll concentrations observed during the simulation period were approximately 100 µg/l. Of course, both the individual effects of photosynthesis and respiration as well as the net effect will be dependent upon the quantity of algae present.

The model's sensitivity to euphotic depth was also investigated and the results closely paralleled to those presented for the photosynthesis rates.

3. Effects of Benthic Demand Rate

Since the units of benthic demand rate include an areal term (ft^2), its effects are closely related to the surface area of the Potomac Estuary. Figure VIII-15 illustrates the resulting DO profiles when benthic rates of 0.0 and 2.0 $gr/meter^2/day$ were assigned. As can be seen, the higher rate significantly lowered the entire profile with the most pronounced differences occurring in the wider downstream areas. However, it did not drastically alter the DO gradients or the rates of depression and recovery.

4. Effects of Reaeration Rate

Of the various DO budget components investigated in this sensitivity analysis, the method by which the reaeration rate is computed, i.e. O'Connor-Dobbins equation, Churchill equation, or USGS (Langbein) equation, was the least important in terms of affecting model output. In fact, the three profiles shown in Figure VIII-16 are coincident, indicating that any of the more commonly used equations for determining reaeration rates should prove equally successful.

EFFECTS OF CARBONACEOUS OXIDATION RATE

DEM D.O. SIMULATIONS

OCT. 1969 DATA

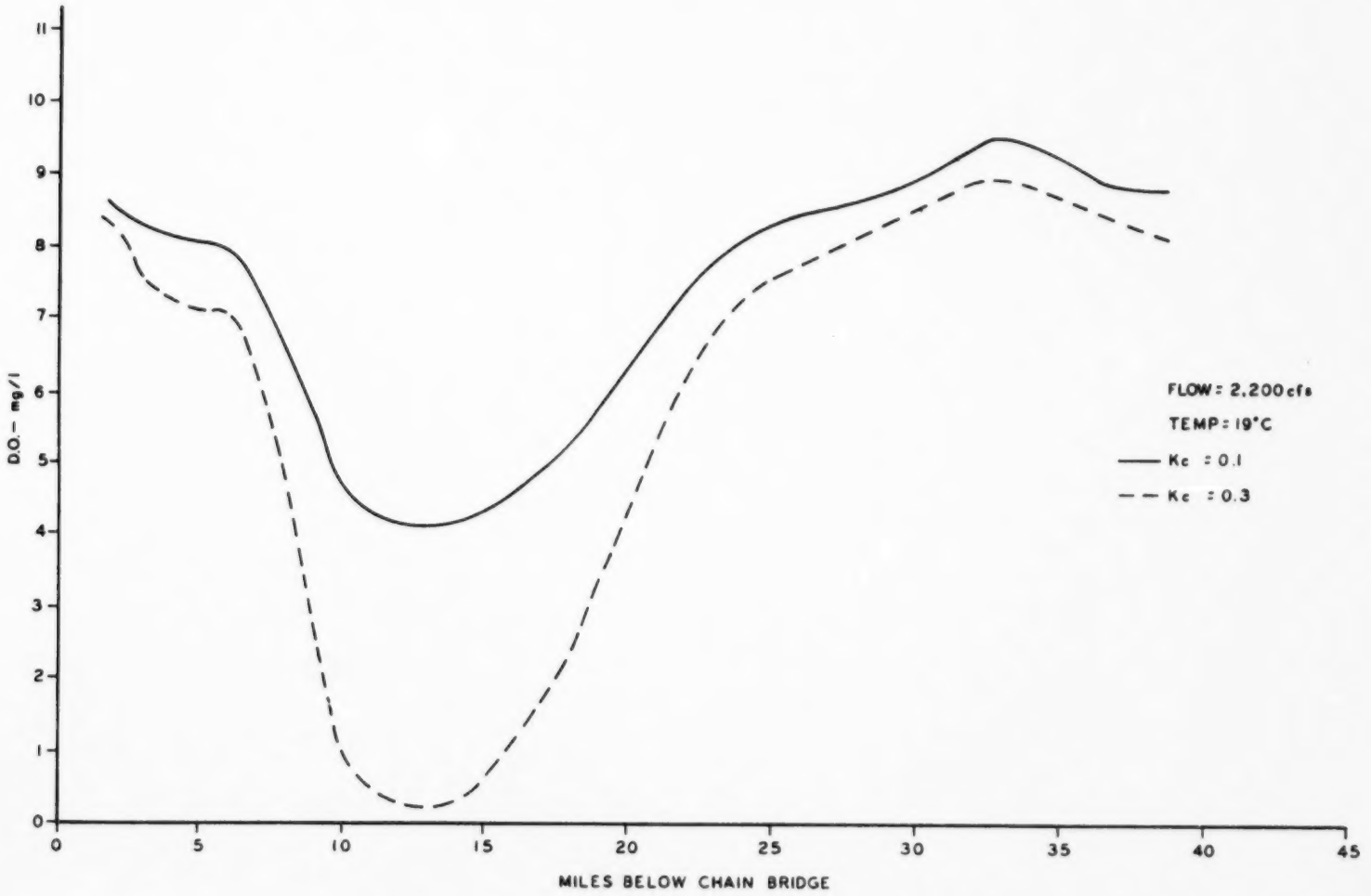


FIGURE VIII-11

EFFECTS OF NITROGENOUS OXIDATION RATE

DEM D.O. SIMULATIONS

OCT. 1969 DATA

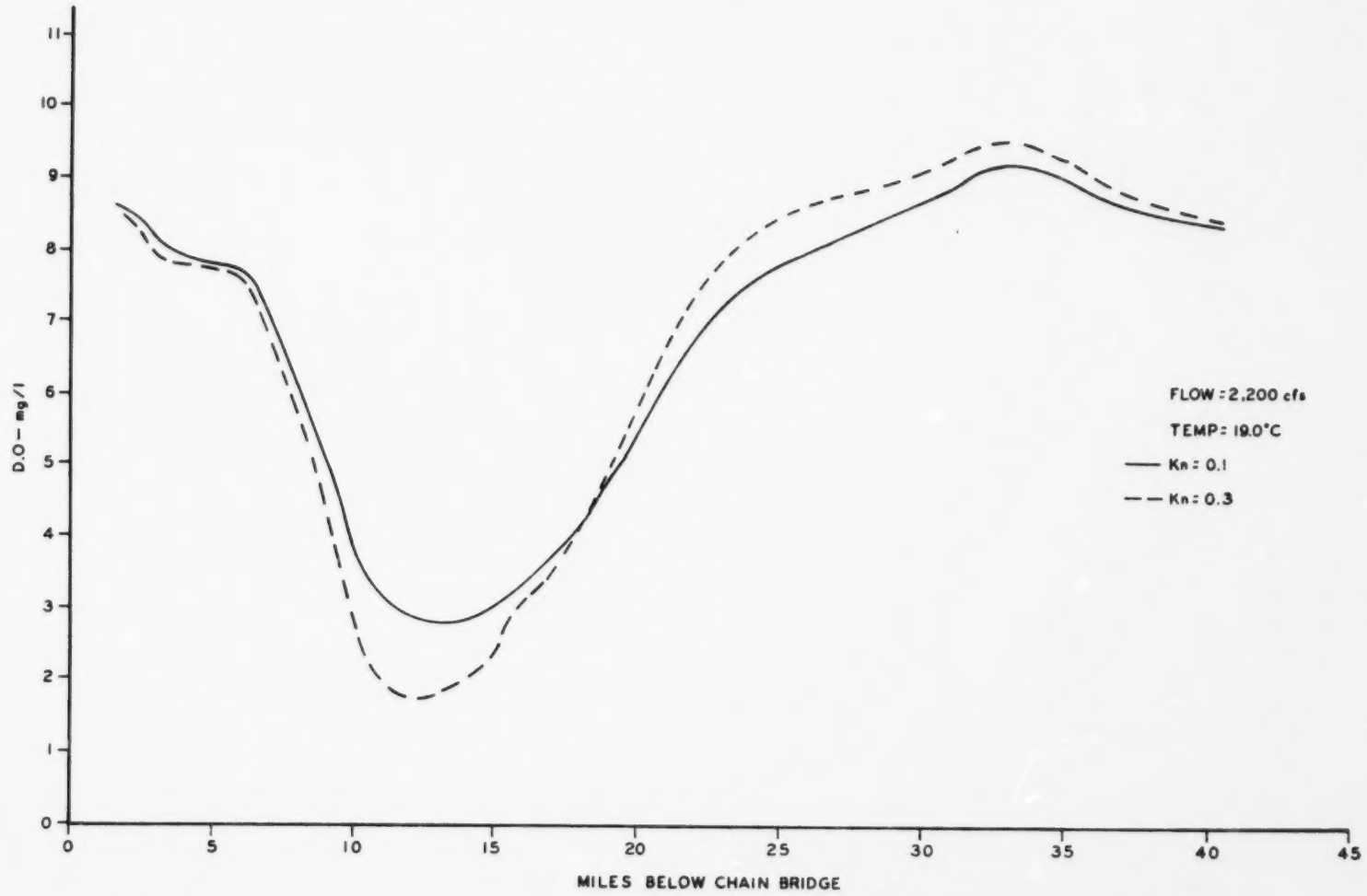


FIGURE VIII-12

EFFECTS OF PHOTOSYNTHESIS RATE

DEM D.O. SIMULATIONS

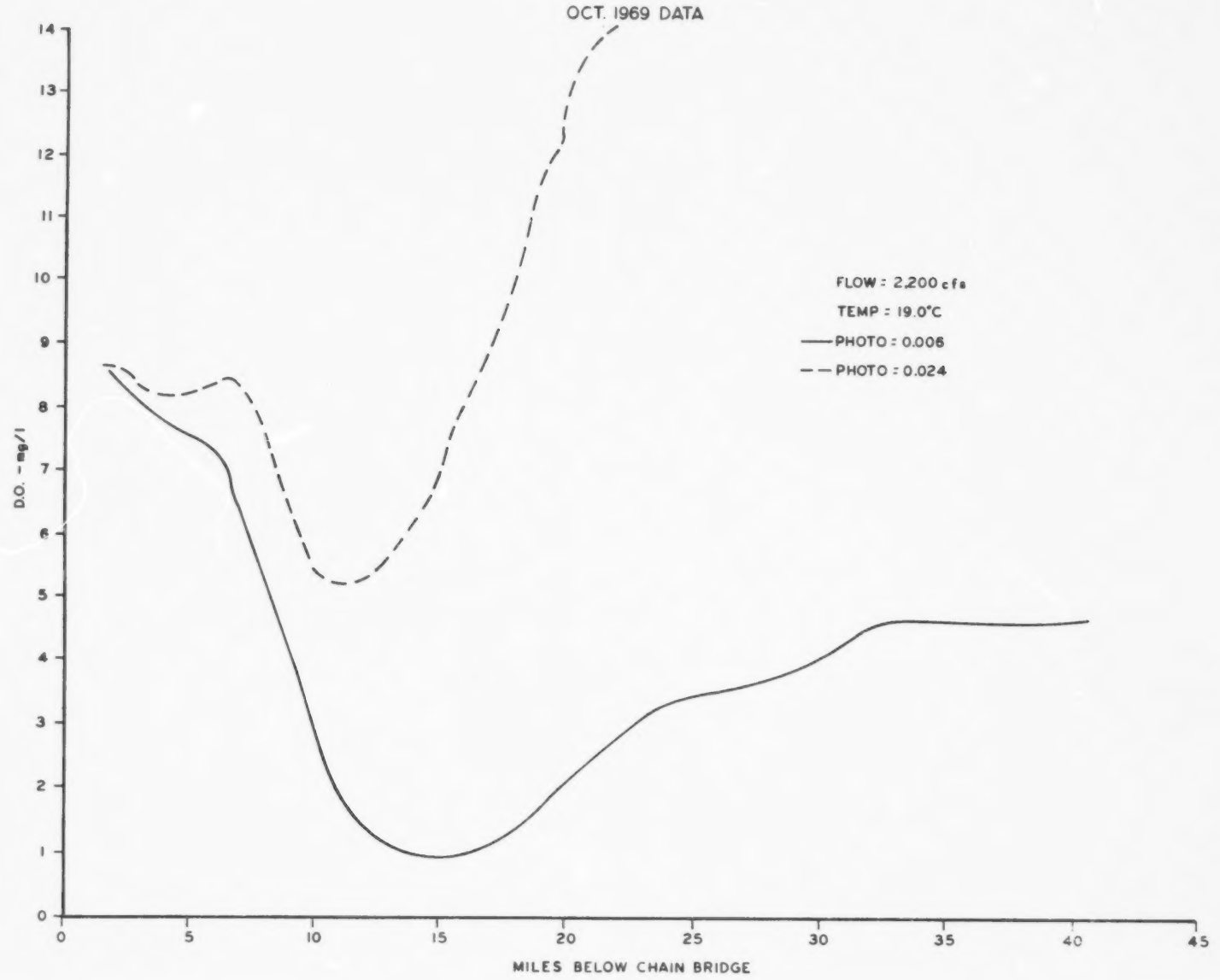


FIGURE VIII-13

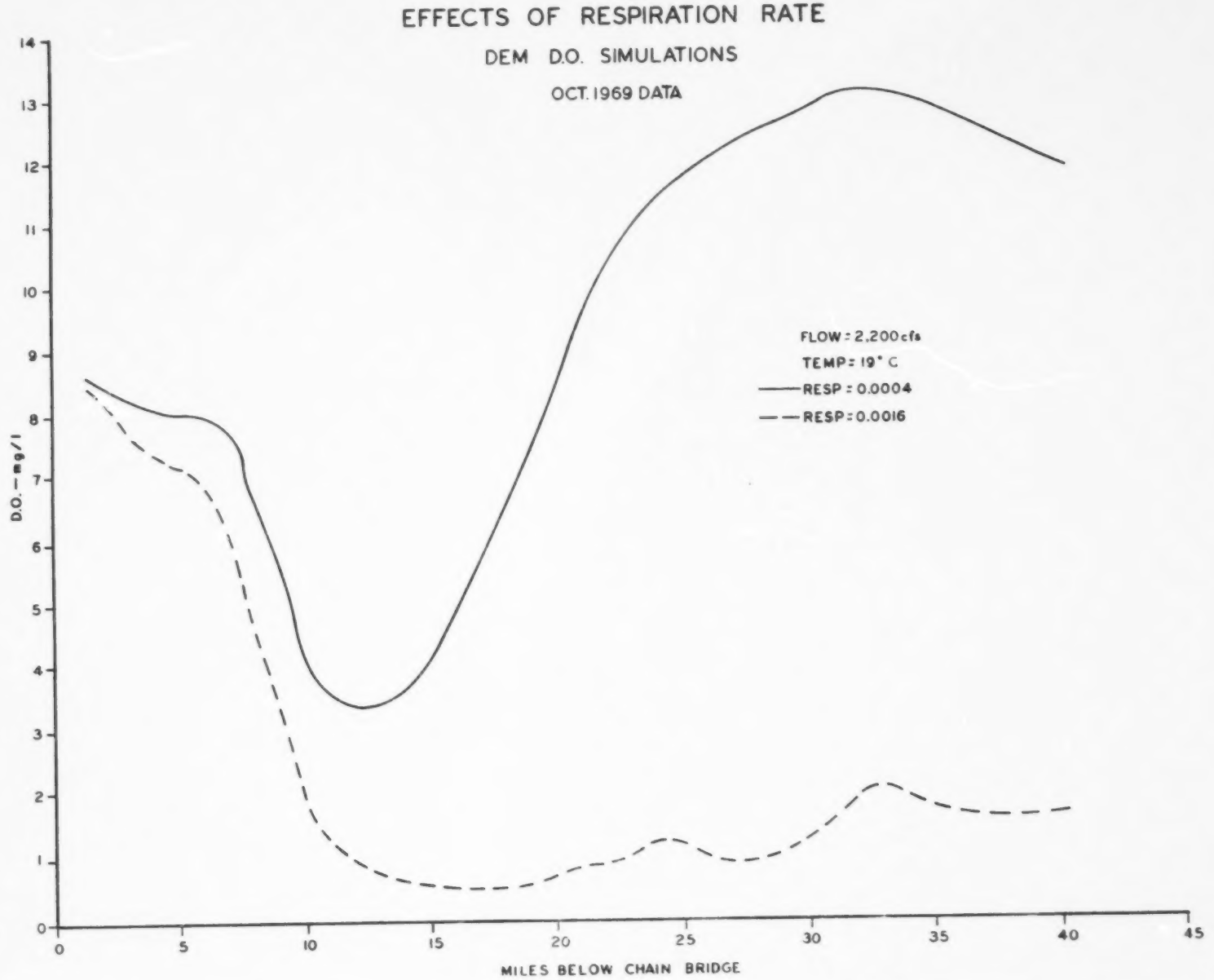


FIGURE VIII-14

EFFECTS OF BENTHIC RATE

DEM D.O. SIMULATIONS

OCT. 1969 DATA

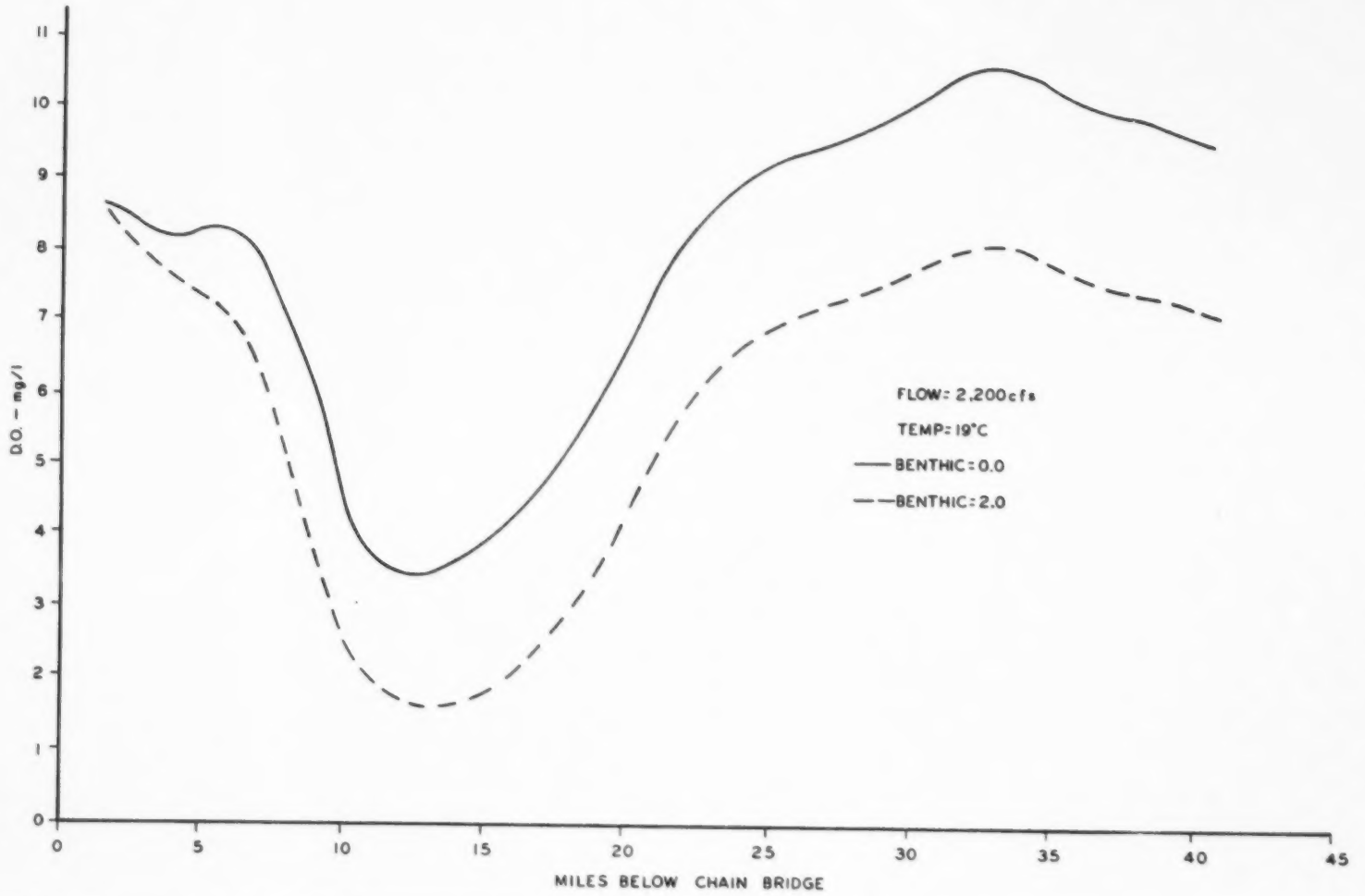


FIGURE V III-15

EFFECTS OF REAERATION RATE FORMULATION

DEM D.O. SIMULATIONS

OCT. 1969 DATA

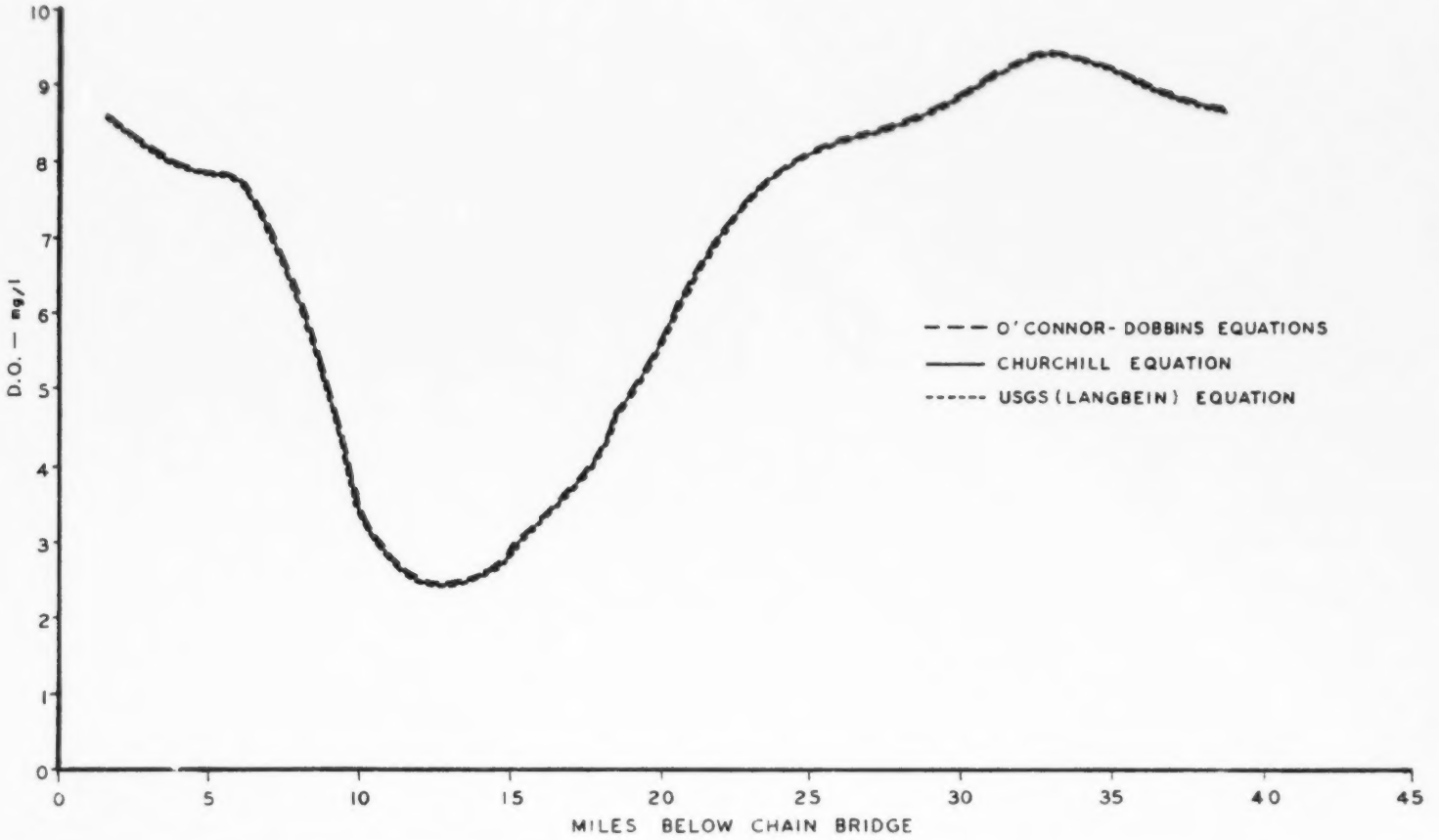


FIGURE VIII-16

D. NUTRIENT REGENERATION - SPECIAL DO MODEL

Realizing the inherent limitations of the dissolved oxygen model heretofore discussed, a further revision of the DEM to incorporate organic nitrogen and nutrient regeneration was investigated. Unfortunately, these inclusions complicated the "feedback-feedforward" linkage within the model somewhat and created a problem by simultaneously evaluating several reaction rates. Prior to this, there had been only a single unknown rate to be evaluated through each series of model verification runs. A considerable amount of background information relating to the nutrient regeneration process was, however, provided by Jewell [13].

Organic nitrogen was treated in two distinct forms in the model: (1) dissolved or soluble and (2) particulate. The latter, or course, would comprise organic nitrogen within algal cellular material. The dissolved fraction was "decayed" by first-order kinetics to ammonia nitrogen (hydrolysis), while a portion of the particulate form was regenerated to inorganic nitrogen (NH_3) and carbon (BOD), thereby creating an additional oxygen demand. Based on a subjective appraisal of existing information, it was assumed that 50 percent of the organic nitrogen and carbon in the dead algal cells, as computed from the mass of chlorophyll decayed, was regenerated; the remaining 50 percent was assumed to be deposited to the bottom sediment. Ratios of chlorophyll to nitrogen and chlorophyll to carbon were estimated using 1970 algal composition analysis data.

Upon completion of this "surrogate" DO model and estimation of the necessary reaction coefficients, a verification run was performed based on September 1970 data. This particular set of data was selected because it pertained to a time of year when algal death was prevalent, as indicated by the relatively high chlorophyll decay rate (0.07/day) required for model verification. Furthermore, a review of Figure VIII-10 shows that the recovery portion of the observed DO profile was not accurately simulated with the existing DO model, presumably because the effects of nutrient regeneration were omitted.

Figure VIII-17 illustrates the improved comparison that resulted from predictions using the mathematical model described herein. Both the rate of recovery and the secondary DO sag farther downstream were satisfactorily simulated. Due to an inadequacy of organic nitrogen data and uncertainties in decay rates, no serious attempt was made to verify the model for prediction of this parameter.

SPECIAL DEM D.O SIMULATION

UPPER POTOMAC ESTUARY

SEPT. 28-30,1970

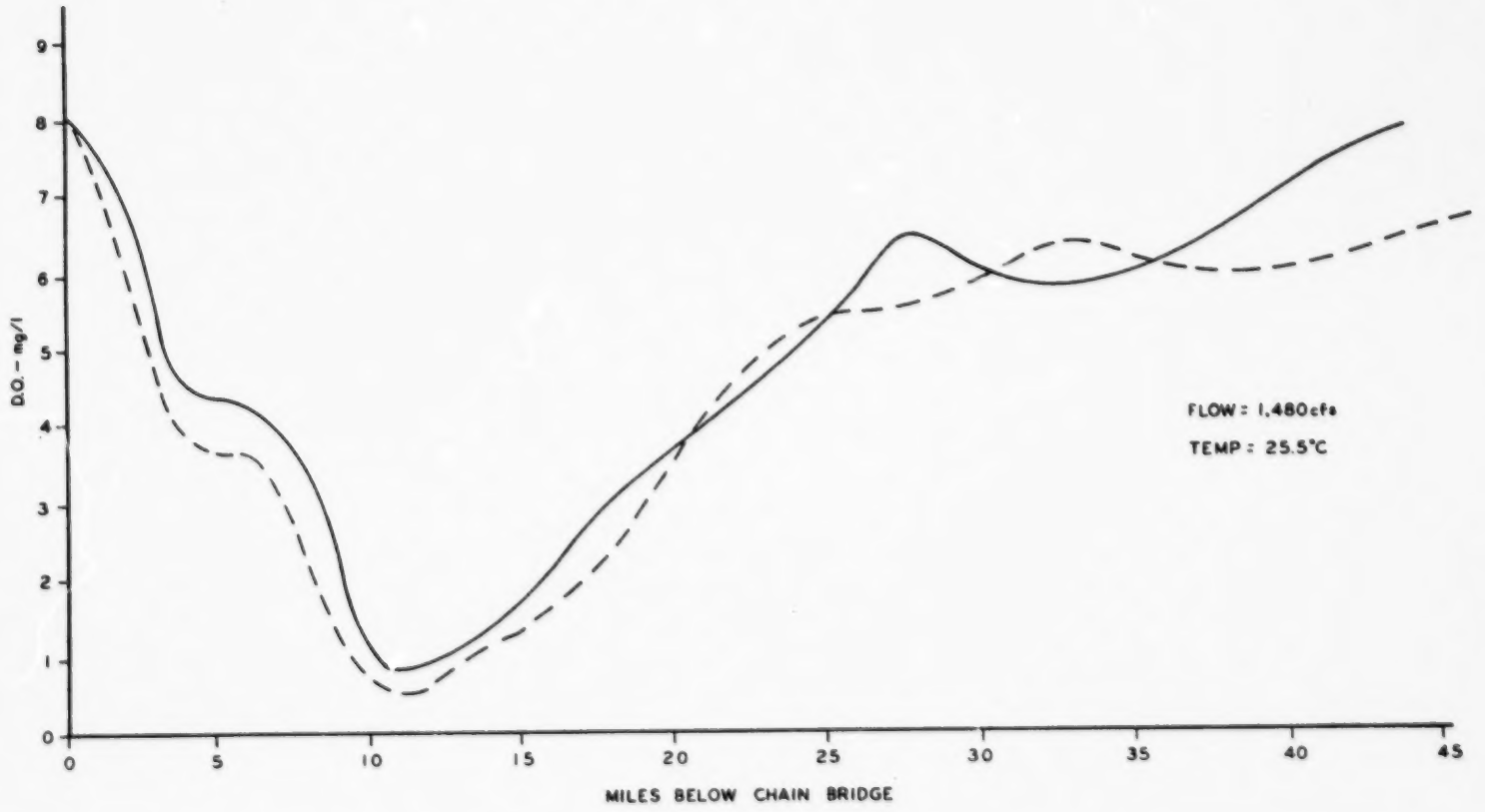


FIGURE V III-17

CHAPTER IX

ADDITIONAL STUDY REQUIREMENTS

Recognizing the basic limitations of existing data and their subsequent effects on model structure and verification, the following areas are suggested for continued study of the Potomac Estuary:

1. The use of either laboratory or field studies to acquire a better understanding of algal decomposition rates and extent of nutrient regeneration,

2. The use of either laboratory or field studies to determine nutrient transfer rates between the bottom sediments and the overlying water for consideration in the overall nitrogen and phosphorus budgets,

3. Perform additional algal composition studies (laboratory) during various times of the year in order to relate biological uptake rates of both nitrogen and phosphorus to seasonal bloom conditions,

4. Develop techniques to acquire a better understanding of the nutrient-phytoplankton relationship in the saline portion of the Potomac Estuary where water quality stresses are becoming increasingly pronounced and where biological communities are quite different from those encountered upstream, and

5. Incorporation of data from the above, and other special studies, into a truly biological model; one not only capable of predicting algal standing crop levels but also capable of simulating algal species succession, including their causes and effects, zooplankton grazing

rates and other well established biological reactions. The development of this type of model would not only serve a definite purpose in the Potomac Estuary, but more importantly it would provide a significant foundation for any mathematical modeling effort in the Chesapeake Bay itself.

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